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The tropopause: discovery, definition and demarcation

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Summary. The present paper recounts the discovery of the tropopause and the lower layers of the stratosphere. It provides an overview of studies of the vertical dimension of the atmosphere prior to the discovery of the stratosphere, and discusses the discovery itself. An account is given of European efforts and the international exchange during this period and this is followed by remarks on its perception during the first decade after the discovery. The historical development of terms related to the tropopause and to the stratosphere is discussed, along with an outline of various definitions of the tropopause — thermal, dynamical and chemical ones — and of the problem related to their use in order to demarcate the tropopause.

Die Tropopause: Entdeckung, Definition, Bestimmung

Zusammenfassung. Die vorliegende Arbeit behandelt die Entdeckung von Tropopause und unterer Stratosphäre. Nach einer Übersicht über die Erkundung der Atmosphäre in ihrer vertikalen Dimension im 19. Jahrhundert wird die Entdeckung der Stratosphäre beschrieben, wobei die während dieser Periode unternommenen europäischen Anstrengungen und der dabei stattgefundene internationale Austausch geschildert werden. Auch wird über die zögerliche Akzeptanz der Existenz einer Stratosphäre in der der Entdeckung folgenden Dekade berichtet. Anschließend wird die historische Entwicklung des Begriffs Tropopause diskutiert. Desweiteren werden verschiedene Definitionen der Tropopause — wie thermische, dynamische und chemische — erläutert und abschließend Probleme bei deren Anwendung zur Bestimmung der Tropopause behandelt.

1. Introduction

About a century ago a remarkable and unexpected discovery was made: Léon Teisserenc de Bort in Paris and Richard Assmann in Berlin discovered the tropopause, both were disinclined to believe it. Hugo Hergesell in Strasbourg attributed it to an instrument error, and Richard Assmann and others were convinced that the isothermal behaviour above 12 km was associated with an observational error induced by radiation. Here a review is presented of various aspects of this important event. Several descriptions of this, arguably one of the most important discoveries in meteorology have been published. For instance the reviews of SCHMAUSS (1952) and OHRING (1964) concentrate on the description of the discovery itself. The present paper discusses the development of scientific ballooning during the preceding years; the international exchange during the period of discovery; and the consequences during the first decade after it. The historical development of the use of related terms is presented as well as the different definitions of the tropopause in terms of physical parameters. This also includes a discussion of continuing problems, linked to the demarcation of the tropopause using measured data.

One might ask if there is a need to study the historical development of special branches of sciences. The history of science is itself of intrinsic interest. One readily learns that the results of scientific work depend not only on the work itself but are also influenced by human factors. Scientists suffer from vanity, jealousy, inordinate ambition and rivalry. Besides the ability of individuals, the results also depend on the effect of international competition which under favourable circumstances might provide a climate of cooperation and not that of rivalry. Additionally, it is interesting to study the reasons why individuals, institutions and nations do or do not participate in certain research fields.

One lesson is that the development of science is not always as logical as it is normally presented in its facts. Much was developed by luck, by chance or by favourable conditions or was suppressed or forgotten due to bad luck and unfriendly conditions. In hindsight very often a particular development might be seen as a logical sequence whereas during the period of the development itself it was not that obvious. For young students, admiring the monument of science, it sometimes seems impossible to add another piece of importance to the science by their own work. However recognizing how the monument of science developed, it becomes easier to appreciate the role of individual contributors and, furthermore, that scientists contribute to further the monument, even with small pieces of work.

Another point has to do with the scientific work itself. For instance, the discovery of the stratosphere is characterized by the way the scientific work was performed by Teisserenc de Bort and Assmann. One must emphasize the care with which both scientists unraveled the major discovery from the errors of a very difficult experiment, by means of careful and frequent measurements. They hesitated to publish the results of their work until they were convinced of the quality of their data. This exemplifies a clear standard to guide scientists. For instance, Teisserenc de Bort only accepted all measurements after he had justified those data which he thought were disturbed by measurement errors.

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He used his entire data set after having demonstrated and explained why and how some of the data do not represent real atmospheric structures. Sometimes scientists effect a "partial perception" accepting only data that fit into the preconceived picture but discarding other data.

A strong word a caution was expressed by BERGERON (1959): "... admittedly, the medieval ultra-conservatism of human mind is to-day dispelled, the blind faith in authority is gone, but the tendency may still be there. Moreover, at a given time, the most active scientists and technicians — in the rush of new discoveries and inventions, or their sturdy adherance to old methods or their own convictions — will never be sufficiently aware of their one-sidedness. The only possible, but by no means reliable, remedy would be to try to learn from history".

The paper is structured as follows: Section 2 deals with the history during the period preceding the discovery; Section 3 describes the discovery itself; Section 4 outlines the reception of the discovery and its ramifications during the first ten years; Section 5 discusses terminological issues, outlines the history of the definition of the tropopause and finally a link is made with current scientific work; and Section 6 contains concluding remarks.

2. Investigating the third dimension

The 18th and 19th century is characterized by many attempts to explore and describe the state of the atmosphere in the vertical. A number of factors were usually combined to advance further research and understanding of the vertical dimension of the atmosphere. It was characteristic of this period that some of the motivation for exploring the upper atmosphere arose from theoretical findings. However the main thrust was satisfying one's curiosity and from seeking adventure — may be even publicity. Most aeronautic associations, which were founded later, contained a mixture of wealthy patrons, sporting enthusiasts, military officers, and scientists. Assmann and his aerological observatory in Berlin, for example, worked with Prussian aeronautical ventures. Hergesell, in Strasbourg, enjoyed closed relationship with the local military balloon corps and with Count Zeppelin.

Here is briefly summarized the exploration of the vertical dimension of the atmosphere during the decades before the stratosphere was discovered. This period includes the first manned balloon ascents; the introduction of new sounding balloons and evaluation of its measurement errors; the invention of the rubber balloon; and the first ascents performed with the new system.

2.1. Early investigations

In 1787 Horace Benedict de Saussure climbed the Mont Blanc equipped with a barometer and a thermometer. As a result of this expedition he stated shortly afterwards the simple rule that the air temperature diminishes with height by about 0.7 K per 100 m. Applying this rule, Hermann von Helmholtz and others soon determined that at a height of about 30 km the temperature must approach the point of absolute zero, which opened the way to new questions and increased the interest in exploring and measuring the real temperature structure in the upper atmosphere. With the invention of the hot air balloon in 1783 it became possible to investigate the atmosphere in the vertical. In 1862 James Glaisher and Henry Coxwell, the English aeronauts, became unconscious at 10 km but survived because the aerostat descended shortly afterwards. Fig. 1 shows a contemporary view of this scene. In 1875, this height was nearly equalled by the French aeronauts, Gaston Tissandier, Croce-Spinelli, and Sivel — the two latter were asphyxiated, although a supply of oxygen was carried to assist respiration, see ASSMANN et al. (1899). This and other fatal accidents served to check further high ascents until 1894 when the German A. Berson ascended alone to about 10 km; he inhaled oxygen at times, and suffered little from this extraordinary ascent (ROTCH 1896). Nevertheless, these types of exploration were dangerous, unsystematic and very

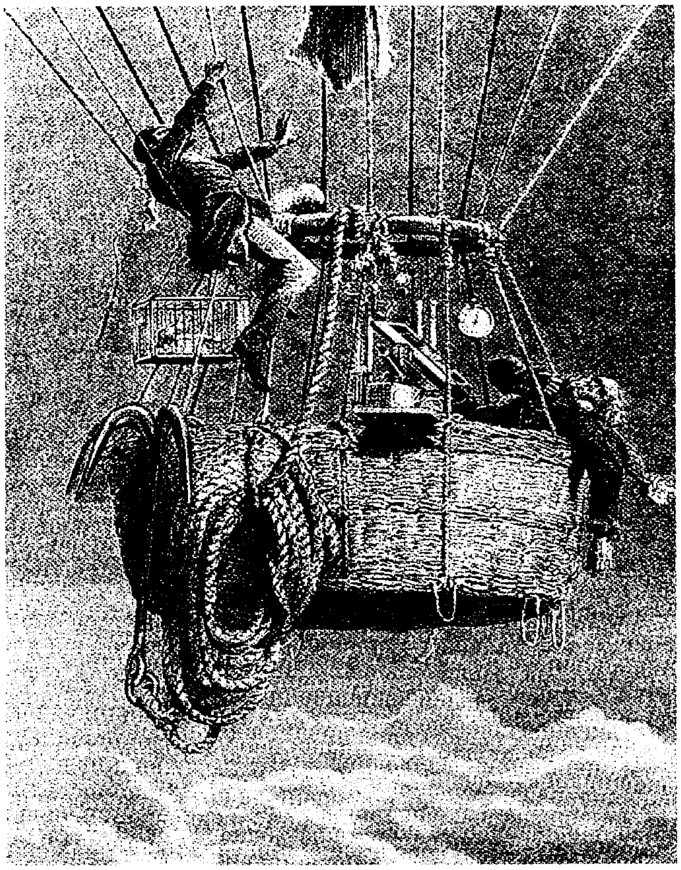


Fig. 1. Contemporary sketch of the dramatic situation when Coxwell and Glaisher became unconscious during their flight in an aerostat in 1862 (taken from FLAMMARION 1885).

Abb. 1. Zeitgenössische Darstellung der Situation während des Ballonfluges 1862, in der Coxwell und Glaisher bewußtlos wurden (entnommen FLAMMARION 1885).

expensive. It is no wonder that the scientific world soon began to seek other methods of studying the free atmosphere.

The atmosphere had been observed from mountain stations for a long time. Therefore, the scientific interest turned to systematically observing the lower atmosphere from mountainous stations. Julius Hann stressed the importance of constructing more meteorological stations in the mountains at the International Meteorological Conference in Rome, 1879. So it was during this period that most European mountain stations were established: Säntis (1882; 2500 m); Pic du Midi (1886; 2859 m); Sonnblick (1886; 3106 m); and Zugspitze (1900; 2962 m). At the same time the station at the Fujiyama (1898; 3720 m) was founded. Some years earlier mountain observatories were built in America: Mt. Washington (1872; 1918 m); Pikes Peak (1872; 4300 m). In the lower atmosphere these new meteorological observations on high mountains began to compete with the observations from aerostats and kites. However, it was soon recognized that the mountains have their own climate which encouraged investigations of the structure of the "free" atmosphere (SCHMAUSS 1933). But the study of the atmosphere by manned balloons, was limited by the height at which man can acquire sufficient oxygen. So, at the turn of the century the interest in observing the atmosphere from mountain stations and aerostats lessened considerably, when a new chapter in history of modern aerological observations was begun. ASSMANN et al. (1899) provides historical details of scientific ballooning during the 19th century.

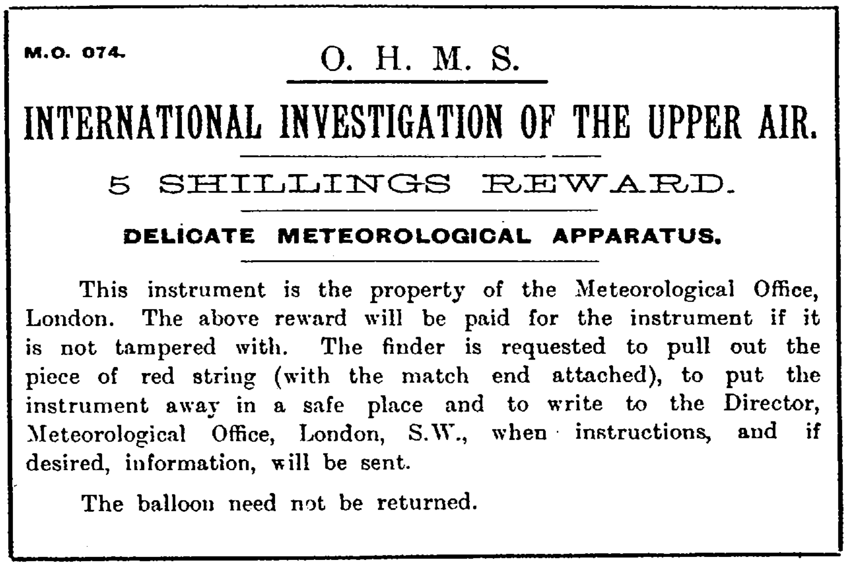
2.2. Invention of the sounding balloons

For many years kites were used in order to investigate the lower atmosphere. It was only a short step from the kite and aerostats to the sounding balloons, which carried a self-recording instrument. This had been suggested by Georges Besançon and Gustave Hermite, the latter a nephew of the famous mathematician Charles Hermite. It was soon recognized that sounding balloons would be a very powerful technique for exploring the upper air (RENARD 1892).

At the beginning balloons were tracked by theodolites, but this allowed only flights in good weather and during daylight. In order to perform night flights, the balloon system was equipped with a light fixed close to the instruments. Later in the century, when the balloons ascended to greater altitudes, tracking by theodolite was impossible and the self-recording instruments had to be recovered after the flight. In order to encourage the public to send back the instruments, an announcement was published (e.g. in the newspapers) with the offer of a reward to the finder if it was returned. Fig. 2 shows an example of this from 1913. At that time, the reward of five Shillings was a considerable amount of money — the averaged weekly workers wage was about three to four Shillings. During the first years of ballooning the return rate was very low, so that RENARD (1893) called these balloons "ballons perdus" (lost balloons). Later the recovery rate increased significantly; at the Conference in St. Petersburg, 1905, a recovery rate of 96 % was reported (QUERVAIN 1905). Then when most of the released balloons were recovered, the name "ballons explorateurs" was given, which afterwards changed to "ballon-sondes", or sounding balloons; the Germans called them "Registrir-Ballons".

2.3. Measurement errors

In general, the early balloon ascents produced rather poor meteorological data, because the temperature and humidity obtained were very inaccurate due to direct insolation, radiation from the heated gas-bag (in case of aerostats), and inadequate ventilation of the instruments. Initially constant volume balloons were used made of laquered paper, treated



M.O. 074.

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INTERNATIONAL INVESTIGATION OF THE UPPER AIR.

5 SHILLINGS REWARD.

DELICATE METEOROLOGICAL APPARATUS.

This instrument is the property of the Meteorological Office, London. The above reward will be paid for the instrument if it is not tampered with. The finder is requested to pull out the piece of red string (with the match end attached), to put the instrument away in a safe place and to write to the Director, Meteorological Office, London, S.W., when instructions, and if desired, information, will be sent.

The balloon need not be returned.

Fig. 2. Announcement of the British Meteorological Office for returning recording instruments from sounding balloons (taken from GOLD 1913).

Abb. 2. Aufforderung des British Meteorological Office zur Rücksendung von aufgefundenen Ballonsonden (entnommen GOLD 1913).

silk or goldbeater's skin, filled with hydrogen gas. Goldbeater's skin is the outer skin of an ox's appendix, which is used to produce gold-leaf. These balloons ascended with decreasing ascent rate with height and finally, after having reached their equilibrium state, moved about horizontally with the wind. This itself reduced the ventilation of the instruments, needed to counteract the effect of radiation. The scientist were greatly concerned with the following measurement errors:

- errors of pressure, and therefore in the height determination, as soon as the balloon was not tracked by theodolites;
- lag of the thermometer;
- radiation error, caused by direct absorption of solar radiation at great heights where the ventilation of the thermometer was inadequate; and
- positioning of the thermometer, which was sheltered by a box in order to protect it by the landing.

The greatest challenges were to protect the thermometers from insolation, and to ensure acquisition of records, notwithstanding the great cold to which the instruments were exposed. In France the "Richard barothermograph" was developed which eliminated the measurement error due to solar radiation. In 1852 John Welsh, the director of the Kew Observatory in England, became the first to use an aspirated thermometer (see KHRGIAN 1970), which anticipated Assmann's idea by many years. In 1894 Assman at the Royal Prussian Meteorological Institute in Berlin motivated the company of Fuess to build a barothermograph in which the thermometer was ventilated; the instrument came into use in the same year. Later, Assmann, who had published his important paper on the aspiration psychrometer (ASSMANN 1892) maintained that he had not heard about Welsh's instrument and that he had not known that this instrument had been used extensively by Glaisher during his ascents.

The news on this new instrument spread fast over the scientific world, see e.g. ROTCH (1895), who acknowledged: "It is due to the German Aeronautical Association, and to Dr. Assmann of Berlin in particular, that more trustworthy methods of observing temperature and humidity were devised. By means of an instrument called the aspiration psychrometer, hung outside the balloon, and in which a current of air is drawn past the bulbs of the wet and dry bulb thermometers, enclosed in polished metal tubes to cut off the direct solar or reflected heat rays, the great error of the ordinary methods are avoided. These arise from the lack of ventilation — since the balloon is relatively in a calm and air may be brought up from the earth in the basket almost like water in a bucket — and from the consequent heating of the thermometer, either directly by the sun or by radiation from the heated gas-bag."

2.4. First ascents of sounding balloons

It is very curious that before the sounding balloons were introduced, balloons were not used for carrying recording apparatus into the upper atmosphere until 1892, whereas sending up unattended instruments on kites had been familiar since 1749. The first instrumented balloon ascent was carried out by Hermite on September 17, 1892. He sent up a free waxed-paper balloon inflated by illuminating gas carrying a minimum-registering mercury barometer (HERMITE 1892). This was in effect the "birthday" of the so-called sounding balloons. On march 21, 1893, Hermite and Besançon sent up a goldbeater's skin balloon, called "L'Aërophile", from Paris. This was the first high-level balloon flight which recorded a temperature of –21 °C at the highest point of the ascent at 14700 m, whereas at a height of 12500 m the temperature was –51 °C. This enormous and paradoxical difference appeared to be an observational error. Hermite ascribed the unexpected high temperature at the highest point to strong heating of the balloon and the instruments by the sun. The Prussian Aeronautical Association („Aeronautische Abteilung des Königlich Preußischen Meteorologischen Instituts") afterwards also experimented with these balloons; and one of them, the "Cirrus", in July, 1894, rose to a height of over 15 km.

In the following years several ascents were performed by Teisserenc de Bort at Paris with the sounding balloon "L'Aërophile" and by Assmann at Berlin with the balloon "Cirrus" (HERGESELL 1897a). The "L'Aërophile" did four flights until summer 1896 reaching heights between 12 and 13 km, whereas two flights were performed with the "Cirrus" reaching heights between 16 and 19 km in 1894. A personal sketch by Lawrence Rotch of the lower- and upper-air research is given in Fig. 3. Descriptions of the early launching activities can be found in HERGESELL (1897a) and ROTCH (1900).

2.5. Invention of the rubber balloon

In the following years the sounding balloons were widely used for obtaining information about the upper atmosphere. Nevertheless, the sounding balloons were considered problematic because they rose until equilibrium was attained in the rarefied air and consequently the ventilation vanished. Paul Schreiber had recommended already in 1886 that rubber balloons should be used, instead of the paper ones generally employed at that time (SCHREIBER 1886); but this suggestion had been forgotten. About 1900, Assmann entirely changed the technique of the sounding balloon by introducing a closed rubber balloon to replace those of paper, silk or goldbeater's skin. Working with the German rubber company Continental in Hannover, Assmann developed the relatively inexpensive, reliable rubber balloons (FELDHAUS 1909). At that time rubberized material was already used in aerostats. But for balloon soundings a further improvement of this material was necessary because of the large expansion of the balloon at great heights and because the material had to be very thin in order to minimize its weight. Similar types of rubber balloon are still used today.

The use of a balloon made of an elastic material has the advantage that, as the enclosed gas expands, the lifting force

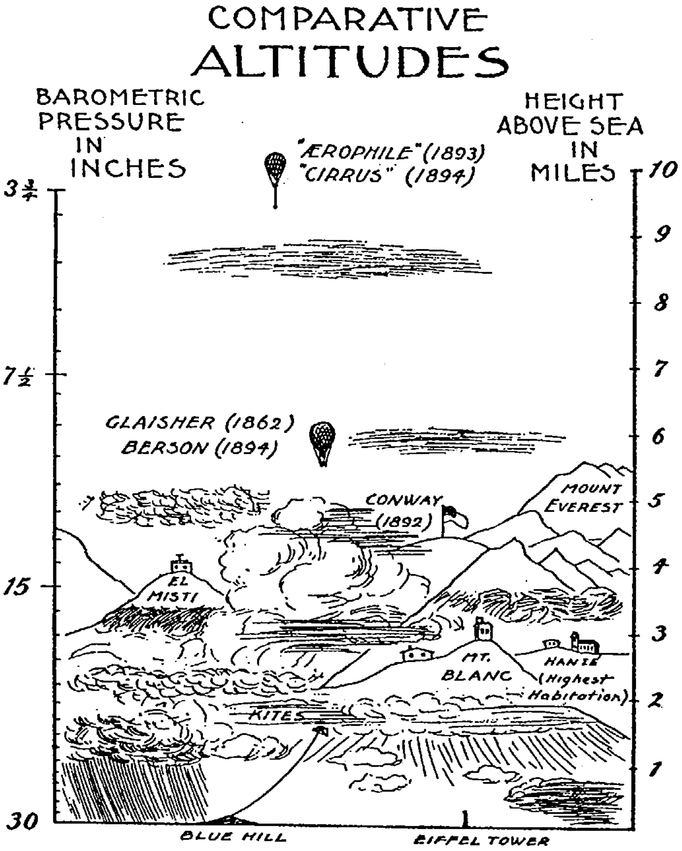

Fig. 3. Upper-air research at the end of the 19th century (taken from ROTCH 1896).

Abb. 3. Zeitgenössische Darstellung der Erforschung der freien Atmosphäre gegen Ende des 19. Jahrhunderts (entnommen ROTCH 1896).

is increased in proportion, so that the balloon rises faster with increasing height until it bursts and then it falls to the ground with diminishing velocity as it is slowed by a parachute. The great advantage of the rubber balloon is that it never reaches a position of equilibrium in which the natural ventilation due to the vertical motion ceases which would allow to the solar radiation to affect the thermometer. After the introduction of the rubber balloons, the method of sounding balloons rapidly came into widespread use. Teisserenc de Bort started to use them during the first years of this century (QUERVAIN 1905). The first theory of launching rubber balloons containing also theoretical considerations was soon provided by HERGESELL (1903).

3. Discovery of the stratosphere — A process of several years

At the end of the 19th century the technique was available for performing precise measurements in the upper atmosphere: sounding balloons were made of rubber and there were improved methods for measuring the temperature, e.g. the aspirated thermometer. However, even using the old technique of paper balloons and temperature measurements allowed reliable data to be collected in the upper air. Here we discuss the international efforts undertaken to perform simultaneous ascents and the establishment of research institutes. That resulted finally in the discovery of the stratosphere.

3.1. First international exchange

As soon as the scientific world grasped that it was possible to reach great heights with the new sounding balloon and at relatively low costs, the method spread rapidly and it proved possible to launch balloons simultaneously from various locations. The idea of simultaneous ascents with aerostats was stated by the French Gaston Tissandier. Later in 1894, the idea of simultaneous ascents of balloon sondes was urged by the German H. Moedebeck in a letter sent to his French colleague Wilfried de Fonvielle (HERGESELL 1898). However, Assmann claimed that he and Berson were the first (HERGESELL 1898). Simultaneous ascents required an agreement about the release time of the balloons. In most reports on ascents of that period the time appeared, e.g. as "Paris time" or "Berlin time". Fortunately, during the geodetic conference in Rome, 1883, the wish was expressed to standardize the time. The USA and Canada accepted the Greenwich meridian to define a mean time, the Greenwich Mean Time. Later in 1893, in Germany the Central European Time (GMT + 1 h) was finally accepted.

From 1893 onwards the investigations acquired an international scale. Several days with simultaneous aerostat soundings were organized between 1893 and 1895, by Pomortseff in St. Petersburg, André in Göteborg, and Berson in Berlin; aerostats were launched simultaneously from St. Petersburg, Stockholm, Berlin, Warsaw and Auschwitz (KHRGIAN 1970). For some times negotiations had been in progress between the French and the Germans to use sounding balloons simultaneously for ascents at night, using identical instruments, whereby the errors due to insolation, and the discrepancies which were attributed to different instruments, would be avoided. Until autumn 1896, Assmann refused to peform simultaneous ascents with his French colleague Hermite, because Assmann wanted to use similar recording instruments in both sounding systems (ASSMANN 1897a). He doubted the French temperature measurements, particularly during "swimming", after the balloon had reached its top height. He favoured the use of his aspirated thermometer. Finally, Assmann accepted simultaneous flights if they were to be done during the night when the radiation error would be small and the ventilation would not be as important a factor.

3.2. Establishment of institutes and international organisations

In Paris, 1896, an "International Commission for Scientific Aeronautics" (IKWL; "Internationale Kommission für wissenschaftliche Luftfahrt") was established at the International Conference of the heads of the meteorological Offices and Institutes. Pomortseff, Rotch, Hermite, Assmann, Cailletet, Besançon, Jaubert, André and Erk were members of the commission. Hergesell was chairman; de Fonvielle was secretary; and Glaisher and Tissandier were honorary members. HERGESELL (1896) hoped to convince an English colleague to join the commissin, but in vain. Surprisingly, Teisserence de Bort was not a member of the board. The reason for this might be that the competition between Assmann in Berlin and Teisserenc de Bort in Paris resulted in some misunderstanding leading to a reduced interchange of information. ASSMANN et al. (1899) later claimed this misunderstanding occurred because Teisserence de Bort felt he was dominated by his German colleagues. The latter expressed this by stating "... on ne se sert pas des abonnements en Allemagne . . .". Nevertheless, it was necessary to appoint a well-respected person as president of the commission. Hergesell from Strasbourg was considered not to be involved in this rivalry and, therefore, was elected president of the commission at the Paris conference. Later in 1898, Teisserenc de Bort became also a member of the commission (IAM 1898). Notwithstanding the rivaly and difference of opinion between the Germans and the French as to the methods of exploring the high atmosphere, there was also a sincere desire to co-operate and the conference in Paris, 1896, furnished an opportunity to make arrangements (ROTCH 1900). The hope was expressed that the effort of simultaneous ascents will be made "... in a spirit of scientific cooperation, rather than of national or personal rivalry" (ABBE 1896). Later, SCHMAUSS (1952) described the cooperation between both, Teisserenc de Bort and Assmann, as a work conducted in a very friendly atmosphere and without rivalry. This is somewhat euphemistic in hindsight because the publications in the journals suggest a different story.

The international commission was set up in order to unify and scientifically regulate the aerological research in Europe (HERGESELL 1896). In particular, it was appointed to unify methods of measurement and to organize experiments with simultaneous ascents the so-called "International Aerological Days (or Ascents)". The first, and one of the most important, experiment organized by the commission was performed with ascents of sounding balloons and aerostats during the night of 13/14 November 1896. The simultaneous balloon flights were made at night in order to minimize the radiation error. The synoptic situation during this night was dominated by a ridge of high pressure between Finland and Austria. Four aerostats participated in this effort and were started from St. Petersburg, Warsaw, München and Berlin; four unmanned sounding ballons were launched from Strasbourg, St. Petersburg, Paris ("L'Aëophile") and Berlin ("Cirrus"). The sounding balloons reached the following heights: 13800 m (Paris), 7700 m (Strasbourg), 5760 m (Berlin), 1500 m (St. Petersburg), the heights were evaluated by Hergesell using the observed temperatures (HERGESELL 1897b). Unfortunately the sounding balloons launched at Strasbourg and Berlin did not reach the expected high altitude because they traversed through a cloud layer which froze the balloon skin resulting in an early descent (MOEDEBECK 1897). It is not clear why ROTCH (1897) commented on these unsuccessful flights by saying: "... owing to hurried preparations only the registration balloon liberated from Paris reached great height...".

The profiles of the nocturnal ascent above Paris on November 13/14, 1896, taken by "L'Aërophile" showed an isothermal layer: at 11700 m a temperature of –51 °C and at the top height at 14000 m a temperature of –53 °C. Because it was thought that the isothermal behaviour was an "error" the measured temperatures were corrected so that the temperature finally was at –68 °C at 14 km instead of the measured value of –53 °C (HERGESELL 1897b). ASSMANN (1897a, b) criticized the temperature measurements and doubted the published values showing an isothermal behaviour above 12 km. A second experiment with simultaneous ascents was performed on February 18, 1897 (HERGESELL 1897c). The balloon launched at Paris reached a top height of 15 km. Unfortunately the instruments and recordings of the flight were partly destroyed because during the landing the sounding balloon touched a telegraphpole. Therefore, the temperature measurements were usable only up to 10 km. The balloon launched at Strasbourg reached 108000 m measuring –55 °C. The balloons from Berlin and St. Petersburg just reached about 3 km.

A very interesting technique was applied during the ascent on this day. In addition to the measurement of pressure, temperature and humidity sounding balloons incorporated another device. By an ingenious apparatus which opened an evacuated glass bulb by breaking a drawn-out point when pressure reached a prescibed level, and immediately closing it again automatically by fusing the broken point, Teisserenc de Bort collected samples of air at different heights and had them carefully analysed for the quantitiy of rare gases in the samples. During the ascent of "L'Aërophile" on February 18, 1897, air was collected at 15 km, which when analyzed showed what was supposed, that at this altitude the composition of the air does not differ much from that of the lower air (HERGESELL 1897c). An extensive description of the experimental results of the first two international ascent days can be found in ASSMANN (1897 a,b), HERMITE (1897) and MOEDEBECK (1897).

The first results of these international days were discussed at the second conference of the commission for aeronautics in Strasbourg in 1898 (IKWL 1898). Fig. 4 shows most of the participants of this conference. Many technical questions were settled, but a significant result was the dissipation of misunderstanding and prejudices, not only between the French and Germans, but between the German representatives themselves; ROTCH (1900) pointed out that ". . . for no doubt personal intercourse is the greatest good of such conferences".

Due to the increasing importance of aerological science, extended research was performed and several institutes were founded. In 1986 Rotch, the founder of the Blue Hill Observatory, commenced a regular series of observations

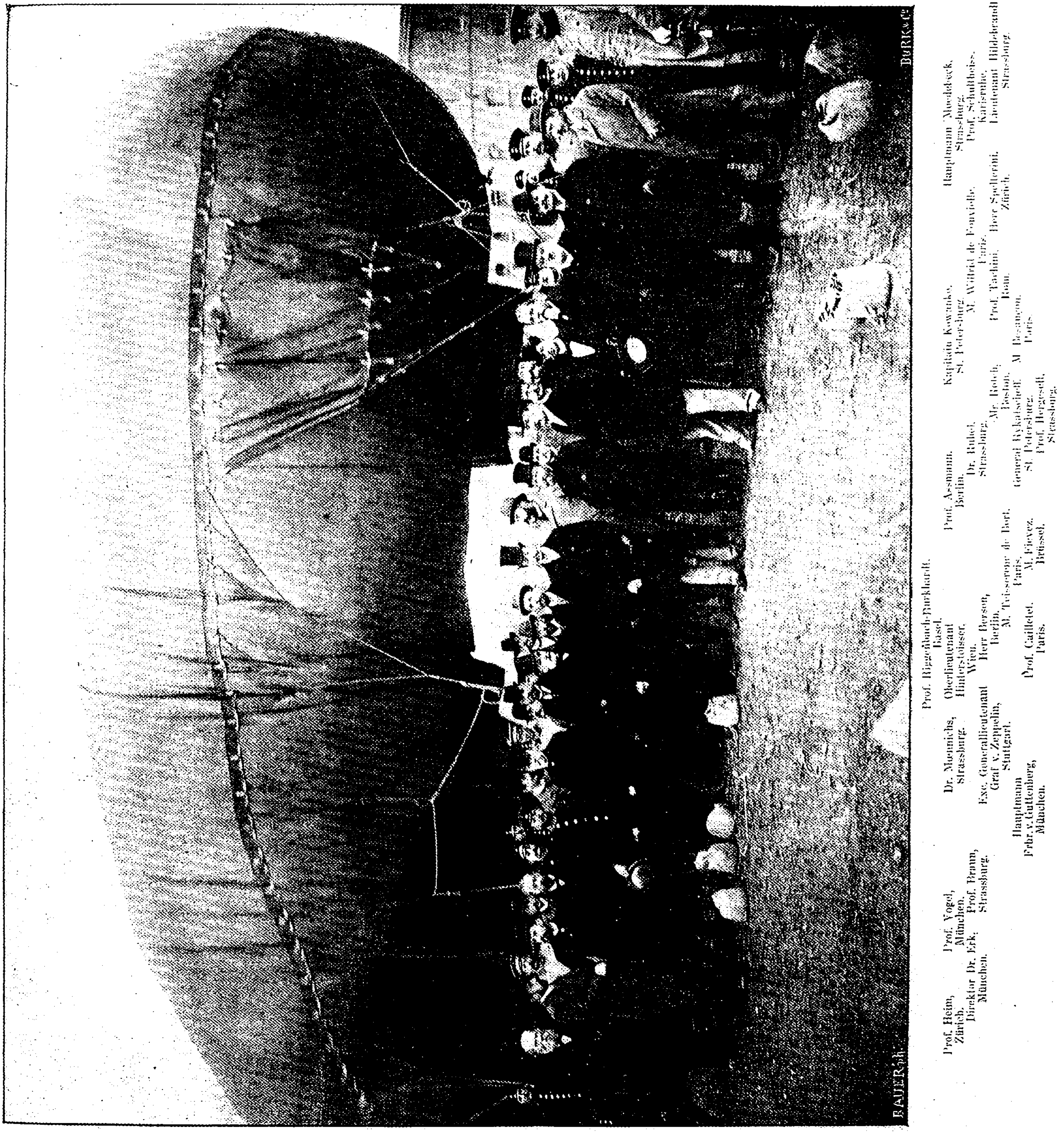

Fig. 4. The participants of the second conference of the Commission for Scientific Aeronautics at Strasbourg on March 31, 1898 (taken from IAM 1898).

Abb. 4. Teilnehmer der 2. Konferenz der Internationalen Aeronautischen Kommission in Straßburg am 31. März 1898 (entnommen IAM 1898).

with self-recording instruments on kites. Teisserenc de Bort founded the aerological station, "observatoire de la météorologie dynamique", in Trappes in the vicinity of Versailles, 1898, for the study of the upper air with kites and sounding balloons. Almost simultaneously, in 1899, Assmann was put in charge of a special section of the Royal Prussian Meteorological Institute, devoted to upper air. He adapted the kite-balloon to carry self-recording instruments; ultimately an observatory for the upper air was established by the German Emperor as a separate institute at Lindenberg in 1905. From 1903 another kite station was operated in Großborstel near Hamburg as outstation of "Deutsche Seewarte" under the direction of Wladimir Köppen (KUTZBACH 1979).

3.3. Publication of the discovery

During the first decade after the first launching of a sounding balloon in 1892, 236 Balloons were launched in Paris ascending to more than 11 km, among these 74 reached heights of greather than 14 km (TEISSERENC DE BORT 1902). During the same period six sounding balloons were launched at Berlin reaching heights greater than 11 km (ASSMANN 1902). The data and a first interpretation of the results of the Berlin soundings were published in three volumes under the auspices of the Aeronautical Society of Berlin (ASSMANN et al. 1899, 1900a, b). It is interesting to note that in these volumes the measurements taken above 10 km are neither discussed nor shown because the studies concentrated taken above 10 km are neither discussed nor shown because the studies concentrated on the behaviour of the troposphere. At that time the best way to publish an outstanding and important scientific result was to present it to an Academy of Sciences. Therefore, the French and German scientists presented the following results of balloon soundings to the corresponding Academy of Sciences:

- — RENARD (1892) in Paris;
- — HERMITE (1892) in Paris;
- — HERMITE (1893) in Paris;
- — TEISSERENC DE BORT (1898) in Paris;
- — TEISSERENC DE BORT (1902) in Paris, April 28; and
- — ASSMANN (1902) in Berlin, May 1.

RENARD (1892) and HERMITE (1892) presented their ideas of launching self-registering sounding balloons by reporting results of several of their ascents. This marks the birth of the new system of sounding balloon. In the next year Hermite presented the results of his first high-altitude sounding which showed the quasi-isothermal behaviour of the stratosphere. However, he doubted the temperature measurements and considered it as an error due to solar radiation (HERMITE 1893). In July 1898 Teisserenc de Bort (Fig. 5) reported three ascents to the French Academy of Sciences that were performed on June 8 and which showed similar isothermal behaviour above the upper inversion. He also doubted his temperature recordings (TEISSERENC DE BORT 1898). To correct the stratospheric values he simply extrapolated the prevailing temperature-height curve from 11.8 to 13.0 km and suggested an actual temperature of –71° for the measured –59° at 13.0 km. Further experiments in 1899 — the first ascent of which was performed on January 8 — showed that this isothermal layer, as he named it, still existed at night, and two years later enough evidence had been collected for him to be able to announce his discovery as clearly established.

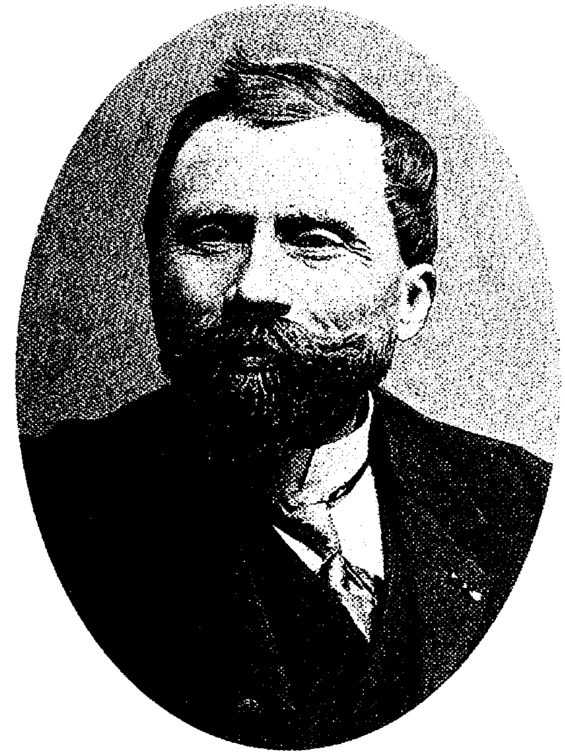

Fig. 5. Léon Teisserenc de Bort (Photo by courtesy of Michel Rochas, Météo-France, Trappes).

Abb. 5. Léon Teisserenc de Bort (Photo mit freundlicher Genehmigung durch Michel Rochas, Météo-France in Trappes).

TEISSERENC DE BORT (1902) presented the results of 236 soundings which had been made in the preceding years. He noted explicitly the existence of a "zone isotherme": "... starting with an altitude that varies between 8 and 12 kilometers, according to the atmospheric condition, there begins a zone characterized by a very small rate of diminution of temperature, or even by a slight increase, with alternations of cooling and warming. We are not able to state precisely the thickness of this zone, but, according to the observations already made, it would seem to amount to at least several kilometers. This is a fact of which we were ignorant up to the present time, and it deserves to be taken into very serious consideration in the study of the general circulation. I ought to add that these results are not in agreement with many previous conclusions that had been based upon very insufficient evidence" (TEISSERENC DE BORT 1902). Additionally he mentioned that "... the altitude of the isothermal zone is in the neighbourhood of 12.5

km in the central portions of the area of high pressure and north of these, but descends to 10 km in the centers of areas of low pressure ...". He refers also to a report which he had given to the French Society for Physics on June 16, 1899, where he said that all possible errors in the temperature measurements had been eliminated and one could now trust the temperature data.

Finally in 1902, Assmann (Fig. 6) presented his results to the Berlin Academy of Sciences where he stated that the proof of an "upper atmosphere warm air current" has been achieved by using the closed rubber balloons and the aspirated thermometer (ASSMANN 1902). These results were based on six ascents made during the day at Berlin between April and November 1901. In his presentation he mentioned that Teisserenc de Bort had made about 500 soundings in Trappes. He doubted the usefulness of Teisserenc de Bort's techniques using paper balloons. However, Assmann's observations, although obtained by a somewhat different method, led to the same conclusions as those which had been reached at Trappes. Finally, Assmann stated in his report that his results go a considerable way further because he demonstrated that the upper atmosphere shows not only an isothermal behaviour but also an increase in temperature with height. However, this was already stated earlier by TEISSERENC DE BORT (1902) in his academy presentation. Additionally, Assmann noted that the top of the isothermal zone is at about 17 km.

Teisserenc de Bort presented his ideas on the existence of the isothermal zone several months before the official announcement of the discovery at the Paris Academy: "I indicated these pecularities (he meant the isothermal zone) for the first time in October, 1901, in a communication to the Luftschiffahrtverein at Berlin, then in a communication to the Meteorological Society of France in March, 1902, and I developed these conclusions in a note to the Académie des Sciences in Paris in April, 1902" (TEISSERENCE DE BORT 1908). Then, at the International Aeronautical Congress at Berlin on May 20, 1902, Teisserenc de Bort again presented the results of his observations on the isothermal zone (ROTCH 1902). The news of this surprising discovery of the stratosphere spread very rapidly through the scientific world. The discovery was considered to be a very important one, so that the academy reports were immediately translated into English by ABBE (1902) who published Teisserenc de Bort's academy report in the American journal Monthly Weather Review and HANN (1902a) presented the German version in the June issue of the German journal Meteorologische Zeitschrift. Assmann's academy presentation was reported in the August 1902 issue of this periodical (HANN 1902b).

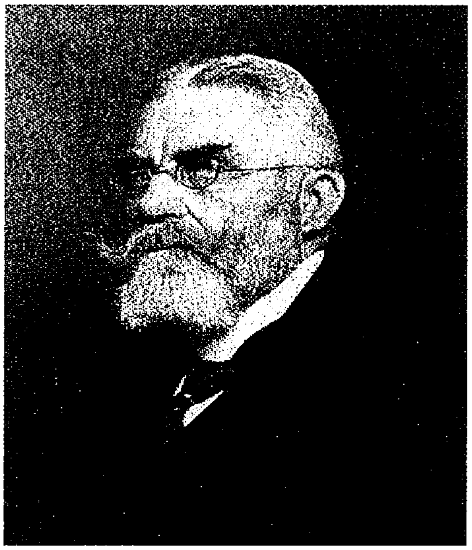

Fig. 6. Richard Assmann in 1915 (taken from PEPPLER 1940).
Abb. 6. Richard Assmann 1915 (entnommen PEPPLER 1940).

3.4. The protagonists during the discovery of the stratosphere

From the publications above described it seems clear that Teisserenc de Bort was the first to state the existence of an "isothermal layer", beginning at about 10 km. Nevertheless, similar investigations establishing the existence of the stratosphere were carried out simultaneously by Assmann. Probably, he published his results only after Teisserenc de Bort had taken the decisive step of declaring the upper temperature inversion to be a rule rather than an exception. It must be emphasized that Teisserenc de Bort unraveled a major discovery by carefully eliminating the errors of what was a very difficult experiment using careful and frequent measurements. This ranks his research as one of the finest in the history of meteorology. The most important contribution of Assmann to this part of the investigation was the introduction of the closed balloon of india-rubber in place of an open-mouthed balloon of varnished paper which Teisserenc de Bort had employed up to that time. Also the construction of the so-called Assmann's aspirated thermometer was an important step forward in providing modern equipment to explore the upper atmosphere. Another question might be who was the first to reach the stratosphere. Hermite and Besançon were the first to observe the upper inversion, which was very marked in their first ascents. But it was considered to be a measurement error. Besides the sporadic attempts by Hermite and Besançon in 1893, Teisserence de Bort reached heights of more than 14 km in seven ascents during the years 1898/99 (TEISSERENC DE BORT 1899).

It is interesting to note how both protagonists, Teisserenc de Bort and Assmann, appear in international encyclopedias. The German Brockhaus (1966) mentions that "... Assmann discovered conjointly with Teisserenc de Bort the stratosphere" whereas "Teisserenc de Bort is one of the discoverers of the stratosphere". The British Encyclopaedia Britannica (1993) acknowledges Teisserenc de Bort's discovery of the stratsophere whereas Assmann does not appear, either as a person or as one of the discoverers. The

Encyclopedia Americana (Americana, 1972) states that "... Teisserenc de Bort . . . found independently of Richard Assmann, that the temperature became constant . . ." in the stratosphere. The French encyclopedia Larousse (1960) mentions that Teisserenc de Bort "... discovered the stratosphere" whereas Assmann discovered it at the same time as Teisserenc de Bort.

One might ask why pose the question as to who was the first to discover the stratosphere? At present mentioning the nationality of the protagonists appears to be obsolete, in particular in an Europe where the members of the scientific community do not attach great importance to the nationality of their members. But at the turn of the century this aspect of scientific life was quite different. Nationality was a very important aspect of (European) society at that time, impinging particularly on work and public life. Therefore, this must be taken into account in the historical context in order to understand the situation and the behaviour of persons, groups and nations. Then, just as today, scientists were not free of vanity, envy and rivalry!

Finally, one should acknowledge briefly the important role of two men during these years of intense upper-air research. The president of the International Aeronautical Commission, Hugo Hergesell (Fig. 7), was a very active and competent scientist. The services which he rendered were twofold. Firstly, he was very successful in forming and securing the international exchange despite the existing rivalry between the French and the German sides. He was also intensely engaged in the launching of sounding balloons from Strasbourg. His active participation in commissions and in scientific work led to him getting the German nickname "Hin- und Hergesell" (WEICKMANN 1938), a pun which can be literally translated into English as "Hither- and Thither-Companion".

Hergesell was also responsible for publishing a series of reports on the meetings held by the International Aeronautical Commission at Strasbourg (1898); Paris (1900); Berlin (1902); St. Petersburg (1904), Milan (1906); Monaco (1909); and Wien (1912). Most of these proceedings were published in Strasbourg and present a good summary of the scientific work which had been done in relation to the upper air research at that time (IKWL 1898, 1903, 1905, 1907, 1909, 1912). The meeting in Paris, 1900, was held during the international meteorological conference (ANGOT 1901). Also with his characteristic care Hergesell published 22 volumes which contain the data of measurements conducted during the International Aerological Days as well as first experimental results (HERGESELL 1901–1912).

The American Lawrence Rotch showed great merit in developing and performing kite obsverations at the Blue Hill Observatory in the USA. He was a close friend of Teisserenc de Bort and participated in experiments which his friend performed in Paris. He also collaborated on experiments done in Berlin with Assmann. He made a distinct contribution by informing the American scientific community about upper-air research occurring at that time in Europe. This can be traced in his translations from French and German journals into English, mostly published in the periodical Monthly Weather Review. Additionally, he published a long list of reports and summaries on meeting and conferences held in Europe on upper air research. Later, ASSMANN (1912) acknowledged that Rotch's outstanding

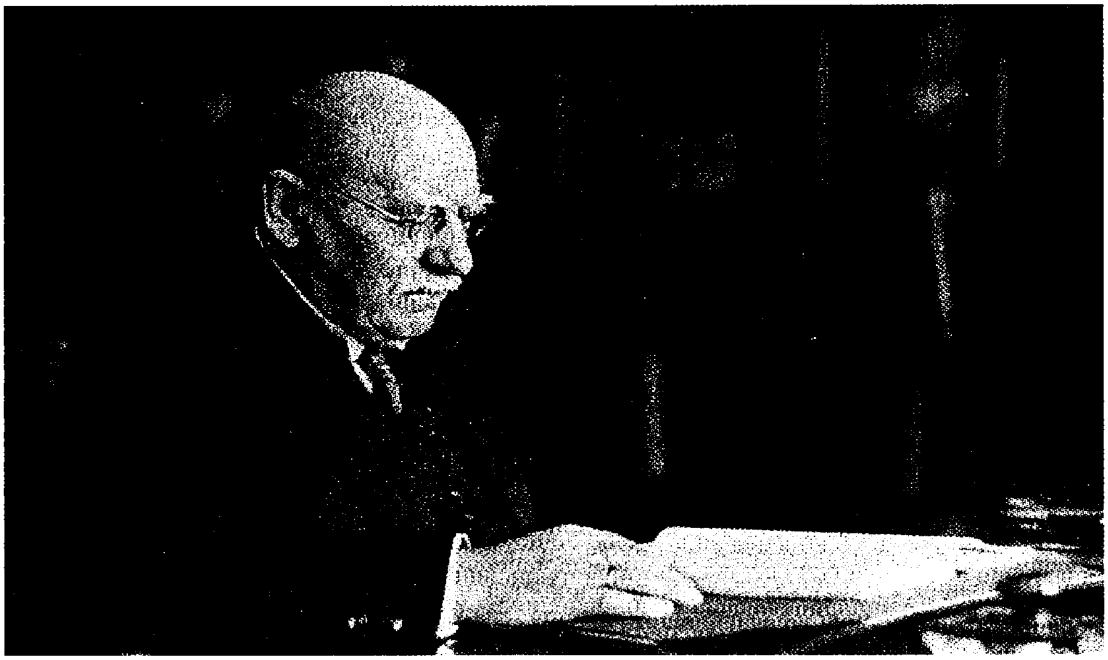

Fig. 7. Hugo Hergesell (taken from Hergesell Festband, 1929).

Abb. 7. Hugo Hergesell (entnommen Hergesell Festband, 1929).

and successful work launching kites at his Blue Hill Observatory was of great support for the founding of the aerological stations in Trappes and Lindenberg. His merits were officially acknowledged during the inaugural ceremony for the Lindenberg Observatory in 1905, when the German Emperor Kaiser Wilhelm II. honored Lawrence Rotch by inviting him to dine (ASSMANN 1912).

4. The decade after the discovery

In this section a review is presented of the activities during the first decade after the discovery of the stratosphere. These includes the experiments performed at various locations around the world; the stimulation for the synoptic view in meteorology; the development of upper-air research in Great Britain; and further facts related to upper-air research during this period.

4.1. Experiments around the world

After the discovery of the stratosphere the next question was whether the phenomenon was observable throughout the year and if so, what its seasonal structure might be. Based on five years of measurements, TEISSERENC DE BORT (1904) showed that the stratosphere was observable during the entire year. He presented the first seasonal mean vertical profiles up to a height of 14 km showing that the annual temperature amplitude close to the surface was about 14 K and in the lower stratosphere about 9 K. By 1904 the discovery of the isothermal layer had been firmly consolidated, although a number of years were to pass before the existence of the tropopause was finally accepted.

Corrobative evidence was accrued during the European coodinated experiment which was performed between 1902 and 1911. During several intense observation periods, the so-called "International Aerological Days", balloons were launched from various European stations: Wien, Berlin, München, Hamburg, Lindenberg, Trappes, Uccle, Milano, Zürich, Strasbourg, Pavlovsk, Kontchiev, Guadalajara, Pavia, Bath and other locations. WAGNER (1910), who conducted 30 balloon ascents between 1902 and 1907, confirmend the earlier findings on the horizontal temperature asymmetry in cyclones, namely that stationary and slow travelling cyclones are generally warm only in their front portion, up to 9 km, and cold in all other sections. However, as pointed out by KUTZBACH (1979), the carefully assembled, detailed results of Arthur Wagner were soon overshadowed by the widely published, equally thorough investigations of William Henry Dines and Ernest Gold. They coordinated the "International Kite and Balloon Experiment" (GOLD 1913). DINES (1911) worked out extensively correlations between pressure and temperature at the surface, at various height levels and at the tropopause based on a sample of about 200 ascents. He found pronounced correlations between surface pressure, temperatures at levels of up to 9 km, and the height of the tropopause. Correlations between surface pressure and temperatures of the stratosphere were negative.

During the first years of this century, a burning question was to clarify whether the upper inversion was a local feature or a global phenomenon. The experiments mentioned above have shown that the upper inversion was not a local feature but was observable over the entire European continent. Very soon after this, aerologists also became interested in more distant places: tropical and polar regions. Therefore, many experiments and expeditions were undertaken to investigate the existence of the upper inversion above the tropics, the polar regions, the mid latitudes, the ocean and above all continents. In 1903 Berson and Elias took measurements in polar regions. In 1906/1907 Hergesell and the Prince of Monaco made an experiment in the area of Spitzbergen. Hergesell was then the first who stated the existence of the upper inversion above the ocean. In 1909, Hergesell also made measurements above Sumatra reaching heights of up to 17 km in the tropical atmosphere. A review of the worldwide expeditions during these years is given in SCHMAUSS (1909).

In North America, kites were used extensively for meteorological observations, e.g. at the Blue Hill Observatory. But the "balloon-sondes" were not tried in America until 1904 (ROTCH 1905a). At the World's Fair in St. Louis, 1904, Assmann exhibited a rubber kite balloon and sounding balloon and all the associated self recording instruments, in particular his aspiration psychrometer, as used in Berlin at the Aeronautical Observatory. In the German Pavilion many self-recording apparatuses were displayed, but perhaps the exihibits of greatest interest were the kites, rubber balloons, kite balloon, and their accessoires (SPENCER 1904). This exibition was a good opportunity for performing upper air measurements. Lawrence Rotch was the first who conducted vertical ascents with sounding balloons. In 1904, he launched sounding balloons in St. Louis, furnished with recording instruments by Teisserenc de Bort and rubber balloons devised by Assmann and constructed in Germany (ROTCH 1905b). Based on these experiments, Rotch proved the existence of the "upper inversion" above the American continent (ASSMANN 1912).

Subsequent observational and statistical investigations yielded a number of results: the tropopause was found to be higher in summer than in winter and higher in the tropics than in the polar regions (TEISSERENC DE BORT 1909). Since the years of the discovery it was known that the tropopause was higher in anticyclones than in cyclones (TEISSERENC DE BORT 1902). The general rule was found that the greater the height of the tropopause the lower the value of temperature. This holds for change with latitude and for change from cyclone to anticyclone.

4.2. Stimulation of synoptic meteorology

At the end of the last century a most important step forward was taken in the system of observation with the introduction of direct aerological soundings. This was done sporadically between 1890 and 1900, and systematically after 1900 under the auspices of the International Aerological Commission. The experiment on 13/14 November, 1896, was the first of numerous such co-operative international experiments which represented the first step in the direction of synoptic aerology: the analysis of simultaneous states of the atmosphere over a large region. The German Wilhelm von Bezold expressed the hope for providing a synoptic picture by use of balloon observations during a talk given in Berlin in 1888: "If it were possible, at different points in Europe, or even just in Germany, to run simultaneous balloon ascents, then in conjunction with the observations taken from ships, lowland and mountain observatories, one could obtain on such a day an image of the atmosphere as we would scarcely imagine at the present time. If it were also possible to apply the synoptic method to the layers at 1000 m, 2000 m, and 3000 m from the earth's surface, this would without doubt result in powerful new progress in our understanding of weather processes."

ROTCH (1900) pointed out that the observations done in 1898 were sufficiently numerous to form a synoptic chart at a considerable height above Europe for comparison with the usual chart drawn from the surface observations. It is interesting to note that there were several efforts to form a synoptic net. However, the results were not very encouraging and came apruptly to an end with the beginning of the first world war. Later in 1959, Tor Bergeron commented that aerological stations equipped with kites and sounding balloons could have formed a real network in Europe and North-America already in say, 1905, instead of that with radiosondes in 1945 (BERGERON 1959).

At the turn of the century meteorologists tended to agree that observations from the upper atmosphere could be useful in order to forecast the weather. After failing to find general laws for forecasting from the weather map based on surface data, they could dream of finding them in the upper-air observations. As a first step, upper-air data were regularly transmitted to the observatories. At the aeronautical conference in St. Petersburg, 1904, Assmann reported that for two years the results of the daily balloon soundings had been immediately transmitted to the Observatory "Deutsche Seewarte" as well as to the newspapers (ASSMANN 1904).

4.3. Upper-air research in Great Britain

As has been shown in Sect. 3, there was a strong European effort to investigate the upper atmosphere during the last decades of the 19th century. It is surprising that in England little was done during the years after Glaisher's epoch-making balloon ascents and that no groups from England participated in the intense upper-air research performed on the continent. In St. Petersburg, 1904, during one of these conferences of the aeronautical commission, it was regretted that England did not show much interest in this field and that no British groups were involved in this research (DE QUERVAIN 1905). This is surprising because several years before, the investigation of the upper air was one of the first items in the programme formulated by the British Meteorological Office in 1877. However, two years later a fatal accident had occurred. The Tay bridge was destroyed by an exceptionally strong gust during a gale on December 28, 1879, while a train was crossing, and the disaster resulted in many deaths. This disaster took much of the meteorologists' attention as they investigated low-level wind structures. At that time kites were adequate to collect data in the lower atmosphere. Among others Dines was very active in this research area. But in the following years, there was only weak interest in observing the upper air in Great Britain. For this, and probably other reasons Sir Napier Shaw stated in 1903: "Meteorology occupies a peculiar position in this country" (SHAW 1903).

A son of William Henry Dines recalled an anecdote which might describe the situation (DINES 1931): "There is a legend, which may be apocryphal, that not long after Sir Napier Shaw took charge of the Meteorological Office in 1900, he and Dines were engaged in friendly discussion of meteorological matters at the latter's home at Oxshott, when the question arose as to the work then going on in America and on the Continent in the measurement of temperatures in the upper air by means of kites. Dines lamented the fact that nothing of the kind was being done in England, and despondently expressed the opinion that he did not know who there was in this country who could be found to undertake such work. Shaw turned round on him with the remark: "Why not you?" Whether or not this be literally true, the following years Dines was very productive in investigating features associated with the tropopause."

In Great Britain the existence of the upper inversion was accepted about ten years later. During this decade there was an intense discussion which occurred in the section "Letters to the Editor" of the journal Nature, between Cave, Draig, Dines, Hughes, Mallock and others. In 1908, Dines called attention to the existence of the isothermal layer pointing out that "... the ascents confirm the interesting theory put forward by Teisserenc de Bort with regard to the existence of a nearly isothermal layer above some 10 km" (DINES 1908). However, not all doubters were convinced. Even at the sixth conference of the International Aerological Commission, held in Monaco in 1909, the British meteorologist C.J.P. Cave cautiously declared that "... in England, too, the existence of an isotheral layer is now assumed to be more and more likely ...". At this, Hergesell as chairman stated that no one of those present doubted its existence and he requested the secretary to enter this fact in the minutes (KHRGIAN 1970).

4.4. Further consequences

The quantity of scientific results in the new branch of meteorology, upper-air research, increased so much that it was necessary to provide a forum for publication. In 1904, a new journal under the title "Beiträge zur Physik der freien Atmosphäre" ("Contributions to the Physics of the Free

Atmosphere") was initiated in Strasbourg by Hergesell and Assmann. The word "free" was chosen to distinguish upper-air research from that done close to and related to the earth's surface. The first paper in the first issue discussed a programme to establish a permanent network of aerological stations. The editorial board consisted of almost all the scientists well known in upper-air research: Cl. Abbe – Washington; W. H. Dines – London; H. Hann – Wien; L. Rotch – Boston; H. Hildebrandsson – Uppsala; L. Palazzo – Rome; M. Rykatchew – St. Petersburg; W. Köppen – Hamburg; and N. Shaw – London. Strangely there was nobody from France who joined this board. The publication of the new journal was immediately acknowledged in America (MWR 1905): "... the periodical itself is bound to become a leading publication in physical meteorology". At that time an extended translation into English was published of the German articles of the first issue.

The development of a new measurement technique results very often in the discovery of a new branch of science. Since the late years of the 19th century the technique of sounding balloons was been developed with great success after the introduction of the rubber balloon and the invention of the aspirated thermometer, both by Assmann. The new branch of upper-air research needed a descriptive name. The word "aerology" itself is very old. As early as 1642 a certain Domenico Panarolo published a book in Rome, under the title "Aerology or a discourse on air. A treatise beneficial to health". However, it was Wladimir Köppen who gave this word the meaning which it has today. In Milan in 1906, at the fifth conference of the International Commission on Scientific Aeronautics, Köppen suggested that the branch of meteorology which uses aeronautical means for the study of the free atmosphere been called "aerology" (HERGESELL 1926). This term then rapidly began to be used widely by scientists.

By 1910 the first period in the development of aerology had been completed. Important discoveries had been made and the technique of aerological ascents had been greatly improved. SCHMAUS (1909) stated: "Today the state of the atmosphere is known up to about 30 km altitude". It then took a long time to explore the layers further up. In 1933, the German Meteorological Society funded an award for that institute which would provide correct temperature measurements up to a height of more than 40 km within the following five years (SCHMAUSS 1933). Presumably, this was forgotten in the well-known political development. At the same time, the invention of the radiosonde in 1927 by Bureau, Idrac and Moltchanoff opened the way to a further development of aerology.

5. Terminology and definitions

Clearly, the discovery of a new atmospheric phenomenon required a definition of what is meant physically by it and a corresponding rule to measure it in terms of physical parameters. The difficulties of definition stem from the many different types of feature which may be measured and therefore named: thermal structure, dynamical factors (wind etc.), concentration of major constituents (e.g. oxygen), concentration of minor constituents (e.g. water vapour, ozone). This section provides a short introduction to the historical development of terms used, of defintions, and of what is meant by the tropopause in terms of physical parameters.

5.1. Terminology

Every succesful sounding revealed a more or less regular decrease of temperature up to a certain height and a steady temperature above that height. The phenomenon was first called "upper inversion" because of its character similar to that known from inversions in the lower atmosphere. Fig. 8 shows an example as published at that time. Due to its temperature structure the layer above the upper inversion was called "isothermal layer". However, it was soon discovered that the "isothermal layer" was hardly ever exactly isothermal, and the name dropped out of general use after a decade. GOLD (1909) pointed out that "... the term 'isothermal layer' is slightly misleading, inasmuch as it appears to produce the conception of a definite stratum of uniform temperature lying between two regions where the temperature decreases at a rate approximately adiabatic. The term 'isothermal region', suggested by Prof. H. H. Turner, is free from this objection."

The most striking property of the layer was then recognized to be its great hydrostatic stability, suggesting that it might be stratified as opposed to mixed, which is the definition of the meteorological term "stratification". This led Teisserenc de Bort himself to suggest the word "stratosphere" for his discovery and the word "troposphere" for the underlying atmosphere (Greek: tropos = turn; troposphere = turning or mixing sphere). Teisserenc de Bort probably coined these terms during the conference of the German Meteorological Society at Hamburg on September 29, 1908, where he gave a talk under the title: "La division de l'atmosphère d'après les résultats de l'exploration de la haute atmosphère" (KASSNER 1909).

Since much interest would obviously attach itself to the boundary between these regions, and since this boundary appeared to be a definite feature, it was not long before a name was found for it, the "tropopause", suggested by Hawke and popularized by Napier Shaw (GOODY 1958). In the fourth issue of the Meteorological Glossary (1918) the tropopause was then simply defined as the "... lower limit of the stratosphere". In the following year, SHAW (1919) used the term tropopause referring to the glossary's definition. In America, shortly afterwards, the term tropopause was also used in the journal Monthly Weather Review by reporting results published in Europe (DOBSON 1920). In a presentation to the Paris Academy of Sciences BJERKNES (1920) refers to the upper inversion by the term "surface de séparation de la stratosphère et de la troposphère" whereas in the English translation of the academy report (MWR

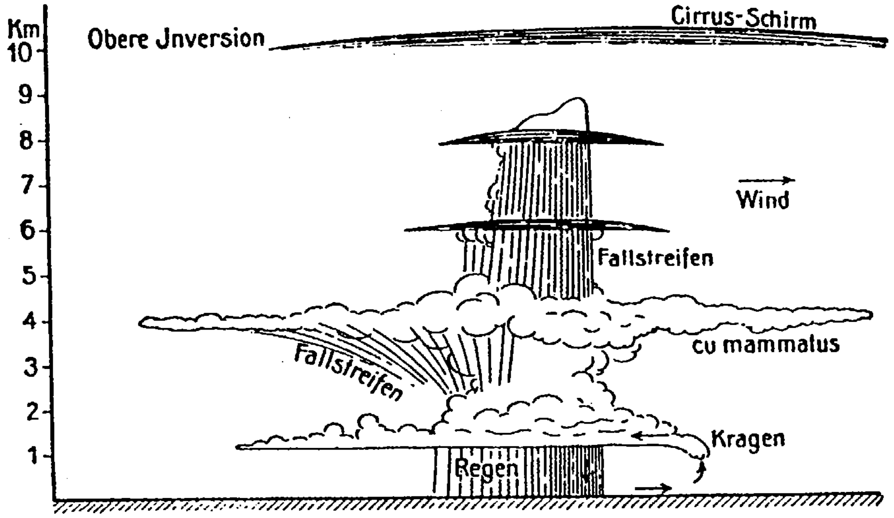

Fig. 8. Image of an ideal storm cloud (taken from WEGENER 1911).

Abb. 8. Ideales Profil einer Gewitterwolke (entnommen WEGENER 1911).

1920) the term "tropopause" appeared. In Germany, it took several years until it was used (HANN 1926).

It was soon recognized that the upper inversion was not a surface but would be better described by the term region or layer. SHAW (1912) used the term "sub-stratosphere" for defining the tropopause layer as a transition layer and SCHMAUSS (1913) then attempted to determine the thickness of this layer. Later FLOHN and PENNDORF (1950) proposed the name tropopause layer. They suggested that the troposphere ends at the lower limit of the isothermal stratum, and not at the inversion. Thus the upper boundary of the tropopause layer is well defined whereas the lower boundary is harder to define. Then in 1962, the WMO recommended the conventional limits between all atmospheric layers, e.g. troposphere, stratosphere, mesosphere etc., which are separated by boundaries or "pauses". The stratosphere, in which the temperature generally increases with height, is here located between the tropopause and the stratopause (SAWYER 1963).

5.2. Definition of the thermal tropopause

The classical rule for the upper end of the troposphere, based on the vertical structure of temperature, was given first by the British Meteorological Office (DINES 1919). The following instructions were issued for defining the level of the tropopause H_c depending on the transition between the troposphere and the stratosphere:

Type I: When the stratosphere commences with an inversion, H_c is the height of the first point of zero temperature gradient.

Type II: When the stratosphere begins with an abrupt transition to a temperature gradient below 2 K per km without inversion, H_c is the height of the abrupt transition.

Type III: Where there is no such abrupt change in temperature gradient, the base of the stratosphere is to be taken at the point where the mean fall of temperature for the kilometre next above is 2 K or less, provided that it does not exceed 2 K for any subsequent kilometre.

Later, in similar form this defintion was then used by the WMO (1957). This operationally used definition of the tropopause is based on the difference in lapse rate of stratospheric and tropospheric air. It is defined as the lower boundary of a layer in which the temperature lapse rate is less than 2 K/km for a depth of at least 2 km. United States weather observers, encoding the results of their rawinsonde observations for teletype transmission, were instructed to select the tropopause level according to the same criteria, but under the restriction that the pressure should be of 500 hPa or lower (U.S. Weather Bureau 1957). The tropopause evaluated using this lapse-rate definition of the tropopause is called the 'thermal tropopause'.

The lapse-rate criteria was operationally used for individual temperature soundings around the globe. It is interesting to note that this objective criterion produced wrong values due to mistakes by the analysist. DEFANT (1958) showed that tropopause pressures ending with the number of '50', or at least '0', seem to be preferred (Fig. 9). A similar "error" was reported by ENDLICH (1954) who showed that the tropopause, as derived from encoded radiosonde data had a very marked preference for the mandatory levels. This indicates one possible source of error in the observed tropopause data.

A recent example is given in Fig. 10. It shows the vertical distribtion of the tropopause pressure observed above München between 1974 and 1993. The left (right) panel shows the distribution based on an increment size of 10 hPa (1 hPa). The distribution with 10 hPa depicts the expected quasi-Gaussian structure with a peak in frequency at about 210 hPa. The distribtution based on a 1 hPa increment size reveals unrealistic strong peaks at the standard pressure levels 200, 250 and 300 hPa. A closer inspection reveals that the sample sizes, e.g. close to 200 hPa, are the following: 149

cases at 197 hPa; 82 at 198 hPa; 34 at 199 hPa; 427 at 200 hPa; 25 at 201 hPa; and 167 at 202 hPa. An averaging between 198 to 201 hPa results in a mean number of cases per pressure level of 142 which is in excellent agreement with the surrounding values at 197 hPa and 202 hPa. Fig. 11 shows the temporal evolution of this "error". During the period of 1974 until 1978 three peaks at 200, 250 and 300 hPa are apparent. Towards the present, until the 84–89 period the peaks at 250 and 300 hPa diminish. Finally in the last period given, the remaining 200 hPa peak decreases significantly in magnitude.

The reason for the unrealistic peaks at the standard pressure levels might be found in the analysis procedure to derive the tropopause pressure from the sounding data. It is standard procedure to evaluate first the values for the standard pressure levels and then to define the significant levels. Finally, the tropopause values are determined based on a data set which contains the standard and significant level data; the original data are not used for this. This might result in stressing the standard level pressure as a tropopause value as soon as the tropopause is very close to one of the standard level pressures.

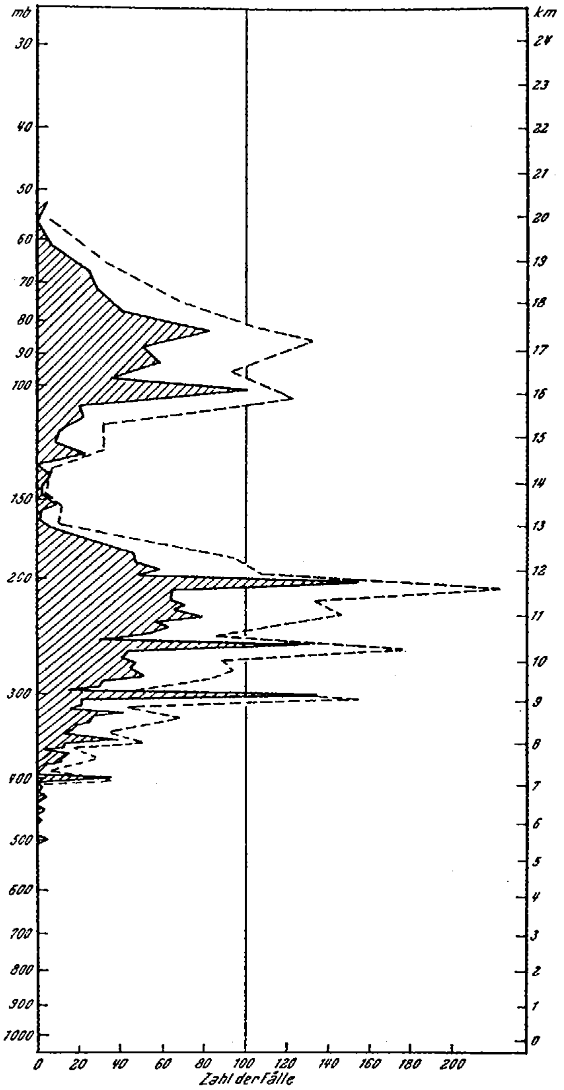

Fig. 9. Distribution of tropopause pressure, January 1956, based on 2500 radiosonde observations of the Northern Hemisphere: Increment 10 (5) hPa full (broken) line. The abscissa indicates the number of cases and the ordinate the height (km) and pressure (hPa) (taken from DEFANT 1958).

Abb. 9. Verteilung des Tropopausendrucks (Januar 1956) für 2500 Radiosondenbeobachtungen auf der Nordhemisphäre: Summierungsintervall 10 hPa (ausgezogene Linie) und 5 hPa (gestrichelt). Die Abszisse zeigt die Zahl der Fälle; auf der Ordinate sind die Höhe (km) und der Tropopausendruck (hPa) angegeben (entnommen DEFANT 1958).

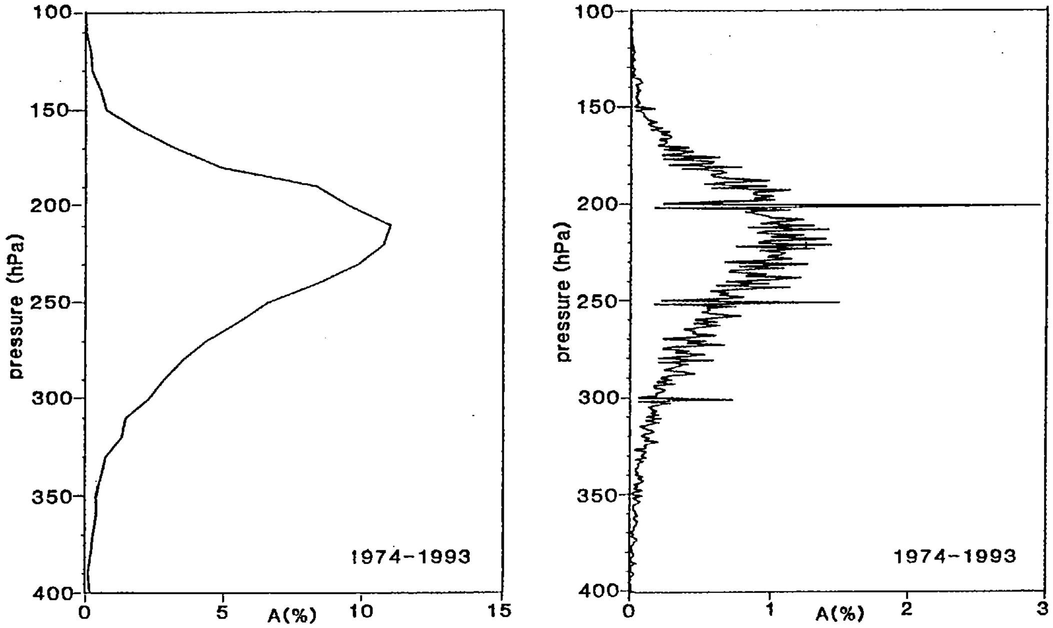

Fig. 10. Distribution of tropopause pressure, 1974–1993 (12 UTC), above München: Left (right) increment 10 (1) hPa.

Abb. 10. Verteilung des Tropopausendrucks über München zwischen 1974 und 1993 (12 UTC): Summierungsintervall 10 hPa (links), 1 hPa (rechts).

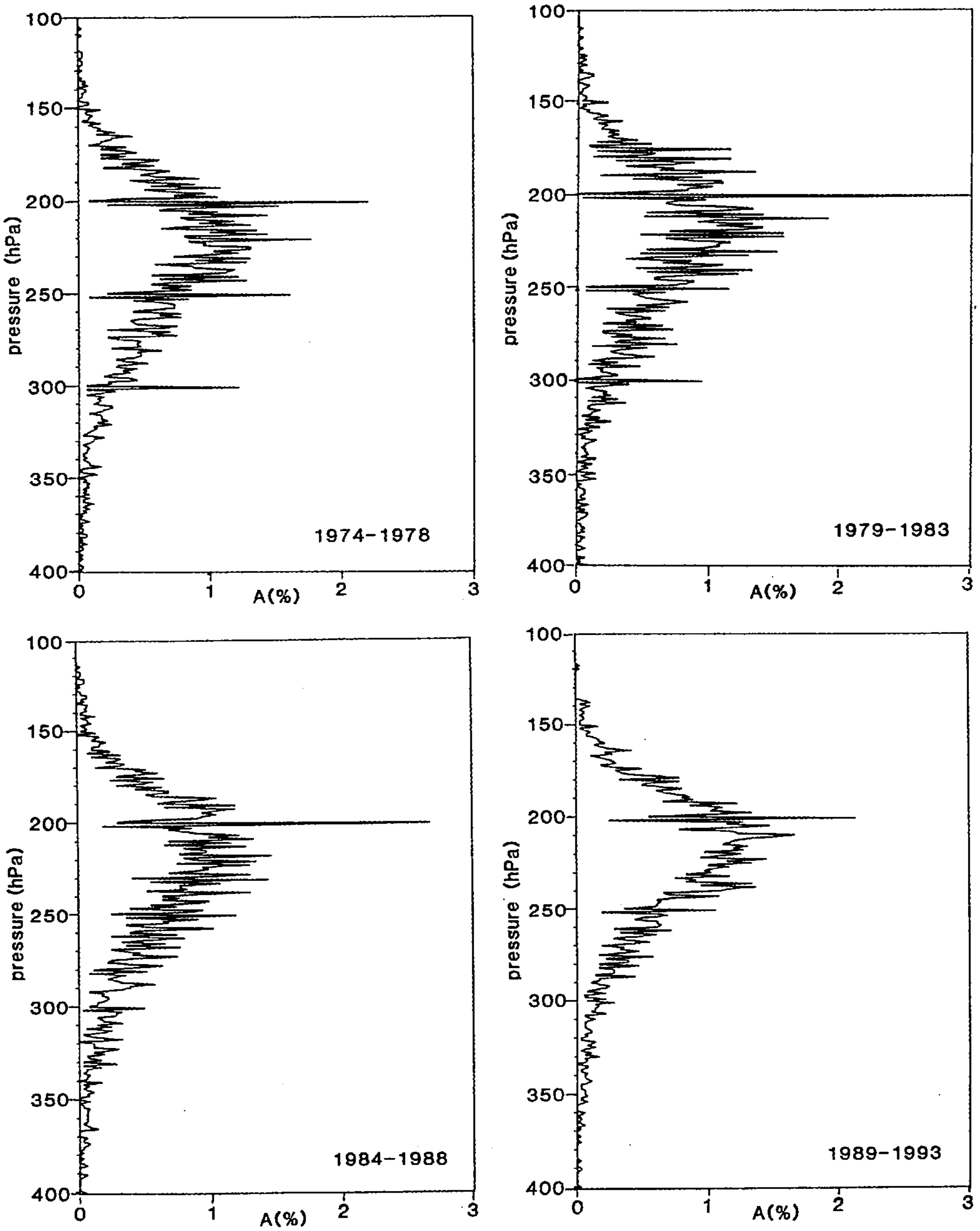

Fig. 11. Distribution of tropopause pressure above München (increment 1 hPa), for various periods of five years: increment 1 hPa.

Abb. 11. Verteilung des Tropopausendrucks über München für verschiedene Fünfjahresperioden (Summierungsintervall 1 hPa).

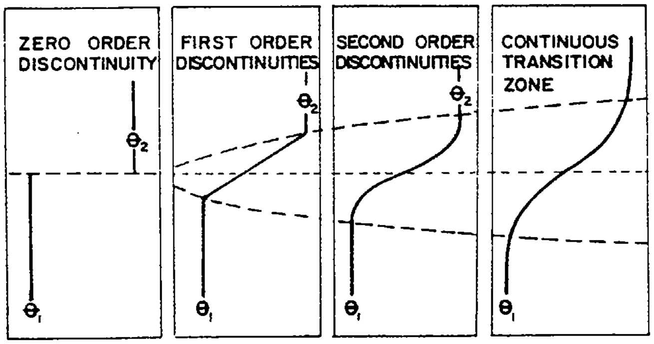

Fig. 12. Discontinuities of increasing order as approximations to a continuous transition zone (taken from Danielsen and Hipskind 1980).

Abb. 12. Die Tropopause zwischen Diskontinuität zunehmender Ordnung und kontinuierlicher Übergangszone (entnommen Danielsen und Hipskind 1980).

Whether this or any other procedure is justified and adequate depends on the true physical nature of the tropopause. Is the transition from the troposphere to stratosphere abrupt or gradual? Is the tropopause continuous in time and space? The ideal boundary between the troposphere and the stratosphere is a single surface of discontinuity of the first order, with discontinuous change of temperature lapse-rate. The different forms of transition possible between the troposphere and the stratosphere are shown in Fig. 12. At the time of the discovery of the stratosphere, it was thought that the "upper inversion" was characterized by a zero- to first-order discontinuity modifying the interchange between the layers above and below. DINES (1911) was the first to pose the question as to whether there is any appreciable interchange of air between the isothermal region and the strata below it. Later Köppen coined the term "Sperrschicht" (blocking layer) in order to describe the effect of suppressing the exchange. Nevertheless, it was soon recognized that the first order description was unrealistic and the term "sub-stratosphere" was then used. Today it is well known that the tropopause may appear in different forms depending on weather and geographical location. In general the tropopause is best described by a transition zone.

Another complication arises from the fact that rather often several points of the ascent curve in the tropopause region may show several discontinuities, so that the lapse-rate changes from the tropospheric to its stratospheric value by successive steps. This so-called "multiple tropopause" (double, triple, etc.) was first observed and described by SCHMAUSS (1909). Fig. 13 depicts an example of a tropopause analysis performed at the end of the second world war. The top panel shows the first analysis done in 1947 where the tropopause along the 80° W meridian is indicated by a full line without breaks (Staff Members 1947). The bottom panel shows a quite different appearance of the tropopause with two break regions (PALMÉN 1948). The tropopause funnel is no more connected with the tropopause itself. In summary one must admit that even with the physical definition of the tropopause given above, in practice the precise definition and location of the tropopause is an arbitrary procedure. There is sometimes a systematic difference of 50–100 geopotential metres between observation on two sides of a national boundary (CRAIG 1965).

5.3. Definition of the dynamical tropopause

With the availability of three-dimensional analysis on the global scale, e.g. analysis of the European Centre for Medium-Range Weather Forecasts (ECMWF), there is a need for an improved definition of the tropopause based not only on thermodynamical lapse-rate profiles but also on dynamical features. One definition of the tropopause, based on potential vorticity, has been proposed by (REED 1955). The isentropic potential vorticity is given by

$$P_\theta = -g\,(\zeta_\theta + f)\left(\frac{\partial p}{\partial \theta}\right)^{-1}$$

where ζ_θ is the relative vorticity along an isentropic surface and f the Coriolis parameter. This tropopause is called the 'dynamical tropopause'. The dynamical tropopause is understood to be a near-zero-order discontinuity in the potential vorticity, which separates low values in the troposphere from high values in the stratosphere. The WMO (1986) defines the tropopause by the value 1.6 PVU, where the PVU stands for 'potential vorticity unit'; one PVU is equal to $1.0 \cdot 10^{-6}$ Km^{2}kg^{-1}s^{-1}. Other studies suggest values of 1 PVU (SHAPIRO 1980) and values between 2 and 3 PVU (DANIELSEN et al. 1987) which qualitatively delineates the location of the tropopause surface.

In view of the uncertainty to apply a particular value of P_θ, (HOERLING et al. 1991) examined tropopause analysis based on the application of several P_θ thresholds. They showed that with the WMO suggested value of 1.6 PVU the tropopause pressures are substantially overestimated. Additional analyses were performed globally using P_θ threshold ranging from 2 to 5 PVU. The tropopause pressure was systematically overestimated for values less than 3 PVU and systematically underestimated for values greater than 4 PVU. Based on the examination of several global analyses during January 1979, a threshold value of 3.5 PVU was suggested by HOERLING et al. (1991) to delineate the dynamical tropopause derived from the ECMWF data. They demonstrated that the use of the isentropic potential vorticity approach provides excellent analyses of the tropopause encountered in midlatitude ridges where objectively determined pressures were generally within 20 hPa of the observed values; also the analyses throughout the development of a continental cyclone were within 20 hPa of the observed pressures. However, strong differences from observed pressure were encountered during periods of rapid development of an upper-level short wave. They emphasized that in general the potential vorticity approach works sufficiently well in the extratropics, however, sometimes difficulties are encountered locally. Because the potential vorticity approach breaks down in regions of small absolute vorticity, tropical tropopause analyses based on this aproach do not work due to possible sign changes of the potential vorticity in low latitudes.

HOINKA et al. (1993) derived the tropopause heights above the Western Irish station Valentia using several different potential vorticity thresholds and by applying the thermal definition to radiosonde ascents and to ECMWF analysis data. They found the best agreement between the distributions of the thermal and dynamical tropopause using a threshold value of 1.6 PVU, although such a definition led to a tropopause "about 30 hPa too low". For the Central European station München a comparison between observed and derived tropopause pressures based on the thermal and dynamical definition is given in Fig. 14. It shows that the observed distribution of tropopause pressure is in good agreement with the dynamical tropopause applying a threshold value of 3.5 PVU (HOINKA et al. 1996). This

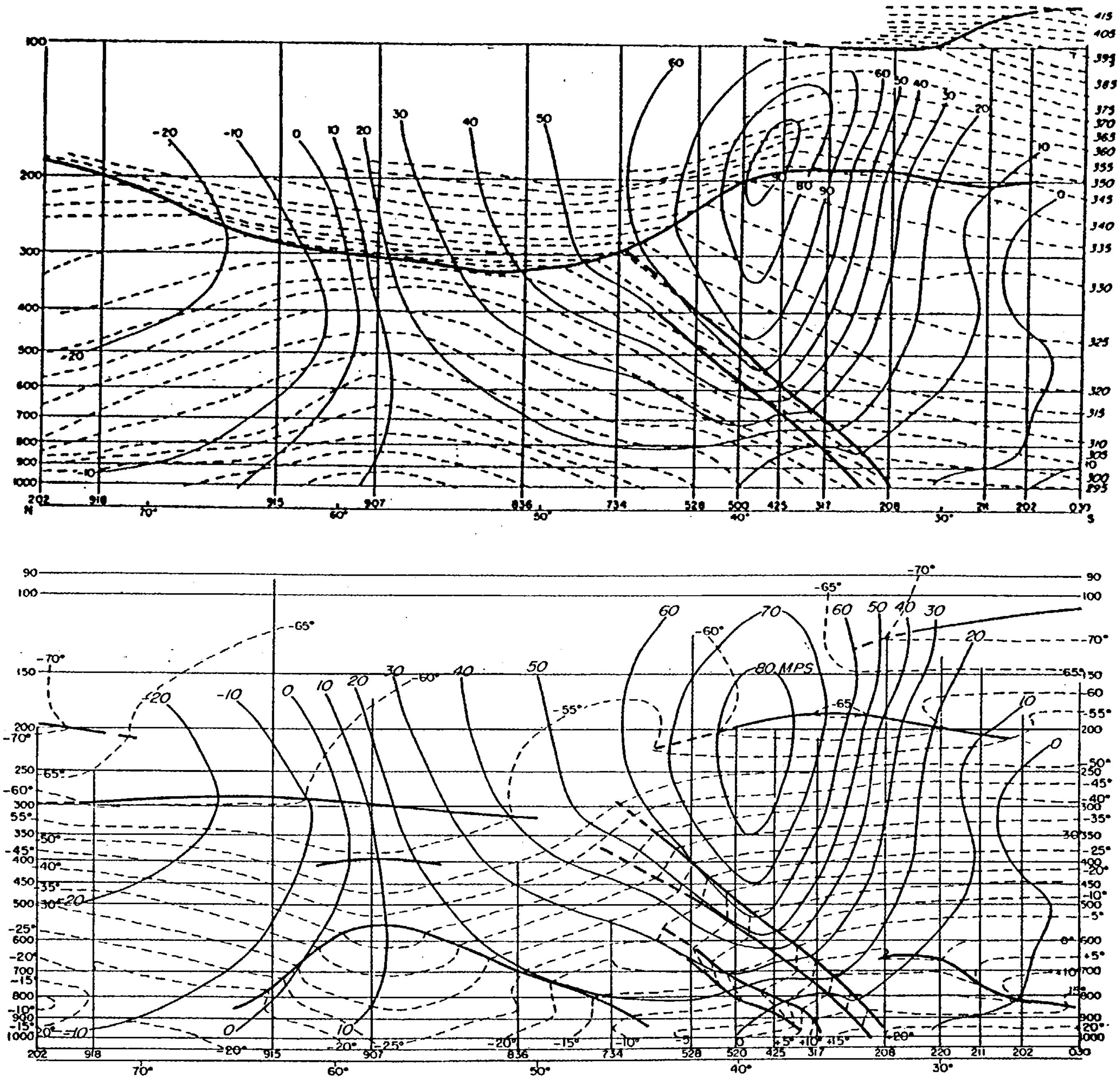

Fig. 13. Meridional cross section for January 17, 1947, 0300Z, from Havanna in the south to Thule (Greenland) in the north. The analysis in the top panel is taken from Staff Members (1947) and that in the bottom panel from PALMÉN (1948). Vertical lines indicate the soundings used in the diagram with the international station numbers below. Frontal boundaries, inversions or tropopause surfaces are indicated by thick, solid lines when they are distinct, and by thick dashed lines, when not distinct. Top figure: thin solid lines represent constant geostrophic wind (westerly wind component in m/s); and dashed lines represent isentropes (K). Bottom figure: thin, solid lines indicate geostrophic wind velocity (m/s) perpendicular to the cross section (zonal wind), dashed lines isotherms (°C).

Abb. 13. Meridionaler Querschnitt entlang dem Längengrad 80° W von Havanna nach Thule (Grönland) vom 17. Januar 1947, 0300Z: die Analyse in der oberen Abbildung stammt von Staff Members (1947), jene in der unteren Abbildung von PALMÉN (1948). Die vertikalen Linien deuten die Sondierungen an, wobei die internationalen Kennzeichnungen am unteren Ende angegeben sind. Fronten, Inversionen und Tropopausen sind mit fetten ausgezogenen Linien gekennzeichnet, sofern sie ausgeprägt sind; andernfalls sind sie gestrichelt. Obere Abbildung: geostrophischer Wind (Westwindkomponente; m/s; dünne ausgezogene Linien) und Isentropen (K; gestrichelt). Untere Abbildung: geostrophischer Wind senkrecht zur Bildebene (m/s; dünn ausgezogen) und Isothermen (°C; gestrichelt).

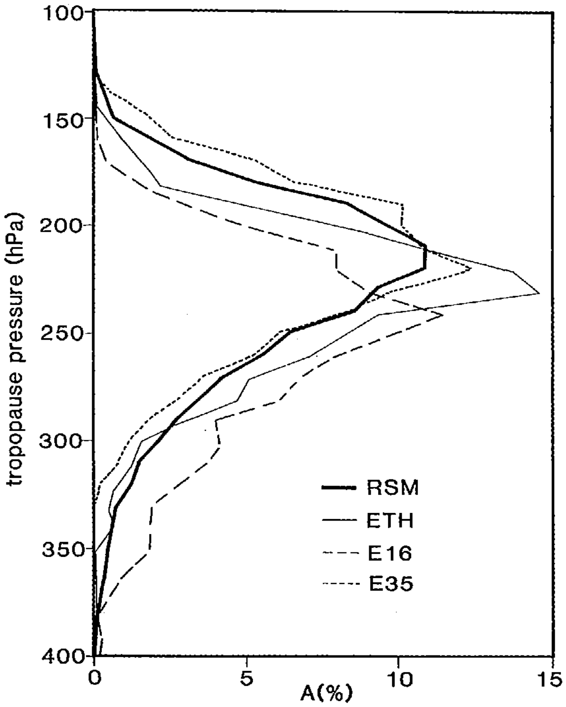

Fig. 14. Distributions of tropopause pressure (increment 10 hPa) derived from rawinsonde observations above München (1974–1993; 00 and 12 UTC; RSM) and those derived from analyses of ECMWF-data (1986–1992; 00 UTC): thermal tropopause (ETH); dynamical with a threshold value of $1.6 \cdot 10^{-6} Km^2kg^{-1}s^{-1}$ (E16) and with 3.5 (E35). The abscissa 'A' indicates the sample size (taken from HOINKA et al. 1996).

Abb. 14. Verteilung des Tropopausendrucks (Summmierungsintervall 10 hPa) über München: Radiosonde (1974–1993; 00 und 12 UTC; RSM) und ECMWF-Analysen (1986–1992; 00 UTC). ECMWF-Analysen: thermische Tropopause (ETH), dynamische Tropopause mit $1{,}6 \cdot 10^{-6} Km^2kg^{-1}s^{-1}$ (E16) und 3,5 (E35). Auf der Abszisse ist der Stichprobenumfang A dargestellt (entnommen HOINKA et al. 1996).

indicates that the choice of the thresholds value in potential vorticity for delineating the tropopause depends not only on the synoptic situation, as pointed out by HOERLING et al. (1991), but might be also a function of the geographical location.

The lapse-rate defined surface has the principal disadvantage of having "... nonphysical, arbitrary and erratic behaviour..." (DANIELSEN 1968). In contrast, the dynamically defined tropopause surface is demarcated by also considering the three-dimensional motion of air besides the stability, as for the thermal tropopause. This provides greater spatial and temporal continuity. Another advantage of the dynamical definition of the tropopause is that the potential vorticity is a conserved property of an air mass which is not affected by diabatic or frictional processes. The thermal definition, however, possesses a major operational advantage in that it allows the determination of the tropopause height from a single temperature profile. From a chemical point of view it is important to know whether either or both of these definitions corresponds to the marked transition in the concentration of trace species that occurs between the troposphere and stratosphere.

5.4. Further definitions of the tropopause

Observational studies suggest that the tropopause often marks the location of an abrupt transition in the concentration of atmospheric properties, including potential vorticity and chemical species, such as ozone, sulfur dioxide, and various oxides of nitrogen (WMO 1986). These abrupt changes suggest that the tropopause is a thin layer separating the stratosphere from the troposphere. As one example, in the following the structure of the ozone profile is used to define a tropopause. BETHAN et al. (1996) investigated the position of the ozone tropopause in relation to the classical definitions of the tropopause. They used about 600 ozone profiles taken from sondes launched at four stations in Northern Europe between 1991 and 1994. The ozone tropopause is defined as the lowest altitude where the following three criteria are met:

— vertical gradient, evaluated over a depth of 200 m, in ozone mixing ratio exceeds 60 ppbv per km;
— ozone mixing ratio is greater than 80 ppvb; and
— mixing ratio immediately above the tropopause exceeds 110 ppbv.

The first criterion was applied because the values of this gradient are generally in the range of 50 to 70 ppvb per km near the tropopause. The second one was chosen because the tpypical ozone/potential vorticity ratio of 40–50 ppbv per PVU at the tropopause corresponds to a range of potential vorticity values between 1.6 and 2.0 PVU which is consistent with the corresponding definition of the dynamical tropopause. The last criterion rejects layers of stratospheric air in the troposphere where the maximum mixing ratio is less than 110 ppvb.

For about 98% of the profiles, the ozone tropopause lay below the thermal tropopause, with an average difference of 780 m. Given that the sondes' finite response time causes a lag of at least 100 m in the detection of the tropopause, the actual average difference between the two types of tropopause was nearer than 1000 m. Where the thermal tropopause was very well defined, however, the average difference decreased to 600 m. Fig. 15 shows the heights of the ozone tropopause versus those of the thermal tropopause.

Additionally, two conditions have been identified where the ozone and thermal tropopause can be of several kilometres apart, and where the ozone tropopause clearly marks the correct base of the stratosphere. In highly cyclonic regions of the lower stratosphere, near the jet stream, stretching of air columns pushes the ozone tropopause well below 10 km. This generates an indefinite thermal tropopause in the corresponding region whereas the WMO criterion is satisfied well above the true tropopause. At high altitudes in winter, the continued decrease in temperature above the tropopause leads to indefinite thermal tro-

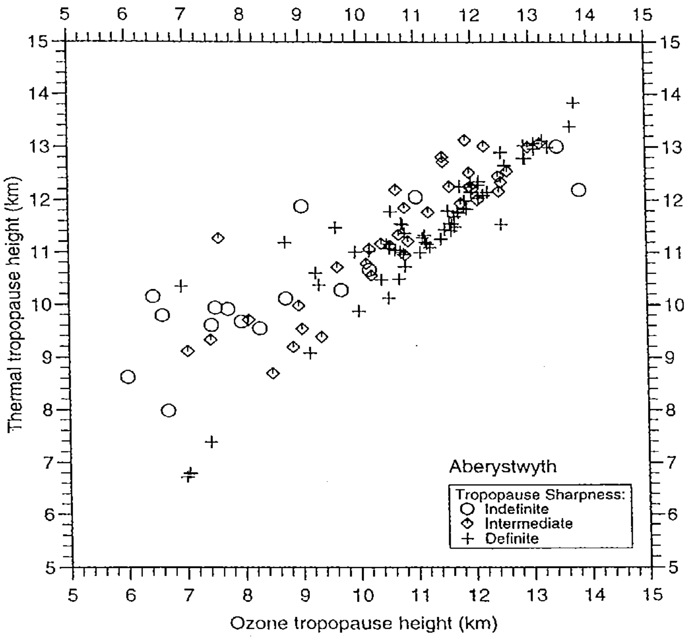

Fig. 15. Thermal tropopause heights as a function of ozone tropopause heights for sondes released from Aberystwyth. Note that the symbols indicate the sharpness of the thermal tropopause (taken from BETHAN et al. 1996).

Abb. 15. Die Höhe der thermischen Tropopause als Funktion der Ozon-Tropopause abgeleitet aus Sondenbeobachtungen über Aberystwyth. Die Symbole kennzeichnen die Schärfe der thermischen Tropopause (entnommen BETHAN et al. 1996).

popauses well above the ozone tropopause. In both cases the conventional thermal definition of the tropopause fails, and the ozone tropopause is unambiguous and sharp. This shows that in special synoptic weather conditions the ozone tropopause might be superior to the thermal or dynamical tropopause. Therefore, it is to be expected that within a short period of time there will be a further official definition of the tropopause released by the WMO based on the vertical structure of zone.

Finally, it should be mentioned that SCHERHAG (1948) proposed a standard level at 225 hPa for constructing a "tropopause chart". This level was chosen because climatological studies on the tropopause indicated that the 300 hPa level above Central Europe was mostly too low (e.g. WAGNER 1936), and that of 200 hPa was located mostly within the stratosphere. However, this chart was only used for a few years.

6. Concluding remarks

The study of the historical development of science can be a source of pleasure, as has been expressed by SCHMAUSS (1934): "As one has a particular delight when one occasionally wanders through the city in which one lives as if one were a stranger to it, so there is a special pleasure in wandering trough the (German) meteorologists' hall of fame which was not created from a master plan, but by free competition which always does such good reconnaissance." We hope that this is in keeping with the present paper which describes the circumstances of discovery of the stratosphere about a century ago. This discovery was not an isolated event but must be seen as one step in the conquest of the physical earth by mankind. Humanity has, for its entire history, attempted to discover and conquer its physical environment. Around 1500 about 25 % of the earth's surface was known. The discovery of America as well as the expeditions of discoverers, like Vasco da Gama, Magalhães, and others, opened the door to enlarge the knowledge of the earth's surface during the following centuries.

At the end of the 19th century about 5 % of the earth's surface was still unknown. At the same time only a small portion in the third dimension, in the vertical atmosphere, was known. At the beginning of the 19th century mankind started to investigate the lower atmosphere where it could be reached by mountain climbing. Later, manned aerostats reached heights of several kilometres above the earth's surface in the free atmosphere. Then, at the end of the 19th century the new technique of sounding balloons allowed the collection of data in the upper atmosphere up to 15 km. The discovery of the stratosphere was therefore the logical consequence of the ongoing examination of the earth by mankind. During the same period, in 1906/07, a deep-sea trough of 9788 m was found in the vicinity of the Philippines. In parallel to the discovery of the physical earth, at the same time the journey towards the psychological interior of man started with the foundation of the psychoanalysis by Sigmund Freund in Wien when his famous book "The Interpretation of Dreams" was published in 1900. Today, mankind has started to escape from the physical earth in order to discover other planets.

In summary, one most say that in meteorology the discovery of the stratosphere is one of the finest events. During the International Aeronautical Congress at Berlin, 1902, Hugo Hergesell noted in relation to the aims of the Commission for Scientific Aeronautics, as expressed in 1898, and on the discovery: "What a tremendous task, but how important the result" (ROTCH 1902). Later, HERGESELL (1904) stated: "... the icy layers of the upper atmosphere contain conundrums enough, to be worthy of humanity's greatest efforts ...". History will judge whether our present scientific efforts and level of funding suffice to match this challenge.

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References

Abbe, C., 1896: Simultaneous balloon ascensions. — Mon. Wea. Rev. **24**, 415–416.

— 1902: The variations of temperature of the free air at great altitudes. — Mon. Wea. Rev. **30**, 316–317.

Americana, 1972: The Encyclopedia Americana. — International Edition, New York.

Angot, M. A., 1901: Congrès international de météorologie. Paris 1900. — 272 pp.

Assmann, R., 1892: Das Aspirations-Psychrometer. — Abh. Königl. Preuß. Meteorol. Inst., **1**, No. 5, 114–270.

— 1897a: Die gleichzeitigen wissenschaftlichen Ballonfahrten vom 14. November 1896, I. — Z. f. Luftschiffahrt u. Physik d. Atmosphäre **16**, 33–39.

— 1897b: Die gleichzeitigen wissenschaftlichen Ballonfahrten vom 14. November 1896, II. — Z. f. Luftschiffahrt u. Physik d. Atmosphäre **16**, 87–98.

— 1902: Über die Existenz eines wärmeren Lufttromes in der Höhe von 10 bis 15 km. — Sitzber. Königl. Preuss. Akad. Wiss. Berlin **24**, 495–504.

— 1904: Über das Aeronautische Observatorium bei Lindenberg. — In: IKWL, 1904. 76–78.

— 1912: Nachruf auf Professor Abbot Lawrence Rotch. — Das Wetter **29**, 73–75.

Assmann, R., O. Baschin, A. Berson, R. Börstein, H. Gross, V. Kremser, H. Stade, R. Süring, 1990a: Wissenschaftliche Luftfahrten. B. **2**: Beschreibung und Ergebnisse der einzelnen Fahrten. — Viehweg, Braunschweig. 706 pp.

Assmann, R., A. Berson, H. Gross, 1899: Wissenschaftliche Luftfahrten. Bd. **1**: Geschichte und Beobachtungsmaterial. — Vieweg, Braunschweig. 150 pp.

Assmann, R., A. Berson, W. von Bezold, R. Börnstein, R. Süring, 1900b: Wissenschaftliche Luftfahrten. Bd. 3: Zusammenfassungen und Hauptergebnisse. — Vieweg, Braunschweig. 313 pp.

Beekmann, M., G. Ancellet, G. Mégie, 1994: Climatology of tropospheric ozone in Southern Europe and its relation to potential vorticity. — J. Geophys. Res. **99**, 12841–12853.

Bergeron, T., 1959: Methods in scientific weather analysis and forecasting. — in: The atmosphere and sea in motion. The Rossby Memorial Volume. Oxford University Press. 440–474.

Bethan, S., G. Vaughan, S. J. Reid, 1996: A comparison of ozone and thermal tropopause heights and the impact of tropopause definition on quantifying the ozone content of the troposphere. — Quart. J. Roy. Meteor. Soc. **122**, 929–944.

Bjerknes, V., 1920: Sur la température des hautes atmosphèriques. — Compt. Rend. Séances Acad. Sci. Paris **115**, 747–750. (English abstract: On the temperature of the upper strata of the atmosphere. — Mon. Wea. Rev., 1920, **48**, 160).

Brockhaus, 1966: Enzyklopädie. — Brockhaus, Wiesbaden.

Craig, R. A., 1965: The upper atmosphere: Meteorology and physics. — International Geophysics Ser. **8**, 509 pp.

Danielsen, E. F., 1968: Stratospheric-tropospheric exchange based on radioactivity, ozone and potential vorticity. — J. Atmos. Sci. **25**, 502–518.

Danielsen, E. F., R. S. Hipskind, 1980: Stratospheric-tropospheric exchange at polar latitudes in summer. — J. Geophys. Res. **85**, 393–400.

Danielsen, E. F., R. S. Hipskind, S. E. Gaines, G. W. Sachse, G. L. Gregory, G. F. Hill, 1987: Three-dimensional analysis of potential vorticity associated with tropopause folds and observed variations of ozone and carbon monoxide. — J. Geophys. Res. **92**, 2103–2111.

Defant, F., 1958: Die allgemeine atmosphärische Zirkulation in neuerer Betrachtungsweise. — Geophysika, **6**, 189–217.

Dines, L. H. G., 1931: The investigation of the upper air: Introduction. — Reprinted in: Collected papers of W. H. Dines, London, Roy. Meteor. Soc., 1931, 117–120.

Dines, W. H., 1908: The registering balloon ascents in England of July 22–27, 1907, preliminary account. – Quart. J. Roy. Meteor. Soc. **34**, 9–11.

— 1911: The vertical temperature distribution in the atmosphere over England, and some remarks on the general and local circulation. — Phil. Trans. Roy. Soc. London. Ser. A, **211**. Reprinted in: Collected papers of W. H. Dines, London, Roy. Meteor. Soc., 1931, 317–344.

Dobson, G. M. B., 1920: Winds and temperature gradients in the stratosphere. — Mon. Wea. Rev. **48**, 160–161.

Encyclopaedia Brittanica, 1993: The New Encyclopaedia Britannica. —London.

Endlich, R. M., 1954: A note on pressure at the tropopause. — Bull. Amer. Meteor. Soc. **35**, 131–132.

Feldhaus, F. M., 1909: Hinauf zur Höh'! — Continental Caoutchouc und Gutta Percha Companie, Hannover. 31 pp.

Flammarion, C., 1875: L'atmosphère. — Spanish version: La atmósfera; translated by Manuel Aranda y San Juan. Barcelona, Montaner y Simon (Eds.). 684 pp.

Flohn, H., R. Penndorf, 1950: The stratification of the atmosphere. — Bull. Amer. Meteor. Soc. **31**, 71–78.

Gold, E., 1909: The isothermal layer of the atmosphere and atmospheric radiation. — Proc. Roy. Soc. London (A) **82**, 43–47.

— 1913: The international kite and balloon ascents.. — Brit. Meteor. Office. Geophys. Mem. **1**, No. 5, 63–144.

Hann, J., 1902a: Leon Teisserenc de Bort über die Temperaturabnahme mit der Höhe in sehr großen Höhen der Atmosphäre (zwischen 8 und 13 km). — Meteor. Z. **19**, 272–273.

— 1902b: Richard Assmann über die Existenz eines wärmeren Luftstromes in der Höhe von 10–15 km. — Meteor. Z. **19**, 384–385.

— 1926: Lehrbuch der Meteorologie. — Herausgeber: R. Süring, Tauchnitz, Leipzig, 867 pp.

Hergesell, H., 1896: Die wissenschaftliche Luftschiffahrt auf der internationalen Meteorologenconferenz in Paris. — Z. f. Luftschiffahrt u. Physik d. Atmosphäre **15**, 241–245.

— 1897a: Der Flug der Registrirballons. — Illustrirte Mittheilungen des Oberrheinischen Vereins für Luftschiffahrt, Heft 2/3, 1–5.

— 1897b: Die Ergebnisse der ersten internationalen Ballonfahrt in der Nacht vom 13. zum 14. November 1896. — Meteor. Z. **14**, 121–141.

— 1897c: Die zweite internationale Ballonfahrt am 18. Februar 1897. — Meteor. Z. **14**, 141–143.

— 1898: Zur Geschichte der internationalen Ballonfahrten. — Illustrirte Aëronautische Mittheilungen, Nr. 1, 22–24.

— 1901–1912: Beobachtungen mit bemannten, unbemannten Ballons und Drachen sowie auf Berg- und Wolkenstationen. — Veröff. d. Internat. Kommission f. wissenschaftl. Luftfahrt. 22 Bände 1901–1912. Herausgeber: H. Hergesell.

— 1903: Über das Aufsteigen von geschlossenen Gummiballons. — Illustrirte Aëronautische Mittheilungen **7**, 163–168. (English translation: On the ascension of closed rubber balloons. — Mon. Wea. Rev., 1903, **31**,571–573).

— 1904: Begrüssungsworte. — In: IKWL, 1905, 28–35.

— 1926: Die Entwicklung der Aerologie. — Meteor. Z. **43**, 322–329. (English translation: the development of aerology. — Quart. J. Roy. Meteor. Soc. **53**, 1927, 75–80).

Hergesell-Festband, 1929: Festschrift zum 70. Geburtstag von Hugo Hergesell. — Beitr. Phys. fr. Atmos., 1929. 278 pp.

Hermite, G., 1892: Exploration des hautes régions de l'atmosphère à l'aide de ballons non montés, pourvus d'enregistreurs automatiques. — Compt. Rend. Séances Acad. Sci. Paris **115**, 862–864.

— 1893: L'exploration de la haute atmosphère. Experience du 21 mars 1893. — Compt. Rend. Séances Acad. Sci. Paris **116**, 766–768.

— 1897: Ascension internationales pour l'exploration de la haute atmosphère. — L'Aërophile **5**, 6–25.

Hoerling, M. P., T. D. Schaack, A. J. Lenzen, 1991: Global objective tropopause analysis. — Mon. Wea. Rev. **119**, 1816–1831.

Hoinka, K. P., H. Claude, U. Köhler, 1996: On the correlation between tropopause pressure and ozone above Central Europe. — Geophys. Res. Lett. **23**, 1753–1756.

Hoinka, K. P., M. E. Reinhardt, W. Metz, 1993: North Atlantic air traffic within the lower stratosphere: Cruising times and corresponding emissions. — J. Geophys. Res. **98**, 23113–23131.

IAM, 1898: Die Konferenz der Internationalen Aëronautischen Kommission zu Strassburg. — Illustrite Aëronautische Mittheilungen, No. 3, 61–65.

IKWL, 1898: Rapport de la commision internationale aéronautique; réunion de Strasbourg 32 mars – 4 avril 1898. — Internat. Kommission f. wissenschaftl. Luftfahrt. H. Hergesell (Ed.), Strasbourg, 138 pp.

— 1903: Protokoll über die vom 20. bis 25. Mai 1902 zu Berlin abgehaltene dritte Versammlung der Internationalen Kommission für wissenschaftliche Luftfahrt. — Internat. Kommission f. wissenschaftl. Luftfahrt. H. Hergesell (Ed.), Strasbourg. 157 pp.

— 1905: Quatrième conférence de la commission internationale pour l'aérostation scientific de St.-Petersbourg, 1904. — Internat. Kommission f. wissenschaftl. Luftfahrt. H. Hergesell (Ed.), St. Petersburg. 211 p.

— 1907: Cinquième conférence de la commission internationale pour l'aérostation scientific à Milan, 1906. Internationale Kommission für wissenschaftliche Luftfahrt. H. Hergesell (Ed.), Strasbourg. 113 pp.

— 1910: Sixième conférence de la commisson internationale pour l'aérostation scientific à Monaco, 1909. — Internat. Kommission f. wissenschaftl. Luftfahrt. H. Hergesell (Ed.), Strasbourg. 161 pp.

— 1912: Siebte Versammlung der Internationalen Kommission für wissenschaftliche Luftfahrt in Wien, 1912. — Internat. Kommission f. wissenschaftl. Luftfahrt. K. und K. Zentralanstalt f. Meteorologie u. Geodynamik, Wien. 172 pp.

Kassner, C., 1909: Bericht über die elfte allgemeine Versammlung und Feier des 25jährigen Bestehens der Deutschen Meteorologischen Gesellschaft zu Hamburg am 28. bis 30. September 1908. — Meteor. Z. **26**, 2–10.

Khrgian, A. Kh., 1970: Meteorology. A historical survey. Vol. **I**. — Jerusalem. 382 pp.

Kutzbach, G., 1979: The thermal theory of cyclones. — American Meteor. Soc. Boston. 255 pp.

Larousse, 1960: Grand Larousse encyclopédique. — Paris.

Meteorological Glossary, 1918: British Meteorol. Office, 4th issue, 358 pp.

Moedebeck, H., 1897: Die internationalen meteorologischen Ballonfahrten. — Prometheus, Jahrg. 8, No. 386, 337–342.

MWR, 1905: Contributions to the physics of the free atmosphere. — Mon. Wea. Rev. **33**, 257–260.

— 1920: On the temperature of the upper strata of the atmosphere. — Mon. Wea. Rev. **48**, 160.

Ohring, G., 1964: A most surprising discovery. — Bull. Amer. Meteor. Soc. **45**, 12–14.

Palmén, E., 1948: On the distribution of tempereature and wind in the upper westerlies. — J. Meteor. **5**, 20–27.

Peppler, W., 1940: Einweihung eines Gedenksteins für Richard Assmann. — Z. f. angewandt. Meteor. **57**, 3–12.

Quervain, A. de, 1905: Bericht über die IV. Konferenz der internationalen Kommission für wissenschaftliche Luftschiffahrt in St. Petersburg. — Meteor. Z. **22**, 22–26.

Reed, R. J., 1955: A study of a characteristic type of upper level frontogenesis. — J. Meteor. **12**, 226–2137.

Renard, Ch., 1892: Sur l'emploi des ballons non montés à l'exécution d'observations météorologiques à trés grande hauteur. — Compt. Rend. Séances Acad. Sci. Paris **115**, 1049–1054. (English translation: On the use of sounding balloons for meteorological observations at great heights. — Mon. Wea. Rev., 1903, **31**, 570–571).

— 1893: Sur l'emploi des ballons perdus pour l'exécution de mesures météorologiques à trés grandes hauteurs. — J. de Phys., Troisieme Sér., Tome deuxième, 63–67.

Rotch, A. L., 1895: Studies of the upper air. — Boston Commonwealth, April 6, 1895, 1–8.

— 1896: The exploration of the air. — Appalachia **8**, No. 1, 180–189.

— 1897: On obtaining meteorological records in the upper air by means of kites and balloons. — Proceed. Amer. Acad. Arts and Sci. **32**, No. 13, May 1897, 245–251.

— 1900: Sounding the ocean of air. Six lectures delivered before the Lowell Institute of Boston in December 1898. — Soc. for Promoting Christian Knowledge, London.

— 1902: The international aeronautical congress at Berlin. — Mon. Wea. Rev. **30**, 356–362.

— 1905a: On the first observations with registration balloons in America. — Proceed. Amer. Acad. Arts and Sci. **XLI**, No. 14 Dec. 1905, 347–350.

— 1905b: Sounding balloons at St. Louis. — Mon. Wea. Rev. **33**, 209.

Sawyer, J. S., 1963: Note on terminology and conventions for the high atmosphere. — Quart. J. Roy. Meteor. Soc. **89**, 156.

Scherhag, R., 1948: Neue Methoden der Wetteranalyse und Wetterprognose. — Springer, Berlin. 300 pp.

Schmauss, A., 1909: Die obere Inversion. — Meteor. Z.**26**, 251–258.

— 1913: Die Substratosphäre. — Beitr. Phys. fr. Atmos. **6**, 153–164.

— 1933: Eine Rückschau auf die deutsche Meteorologie. — Z. f. angew. Meteor. **50**, 261–378.

— 1934: Ein Zeitbild der deutschen Meteorologie. — Z. f. angew. Meteor. **51**, 137–152.

— 1952: Die Entdeckung der Stratosphäre im Jahre 1902. — Meteor. Rundsch. **5**, 1–3.

Schreiber, P., 1886: Bestimmung der Bewegung eines Luftballons durch trigonometrische Messungen von zwei Standpunkten. — Meteor. Z. **3**, 341–345.

Shapiro, M. A., 1990: Turbulent mixing within tropopause folds as a mechanism for the exchange of chemical constituents between the stratosphere and the troposphere. — J. Atmos. Sci. **37**, 994–1004.

Shaw, N., 1903: Methods of meteorological investigation. — Mon. Wea. Rev. **31**, 415–420.

— 1912: Preface to "The free atmosphere in the regions of the British Isles" by W. H. Dines. — Met. Office London, Geophys. Mem. **1**, No. 2, 13–22.

— 1919: Manual of Meteorology. Part IV. The relation of the wind to the distribution of barometric pressure. — Cambridge University Press. 359 pp.

Spencer, J. H., 1904: Three notable meteorological exhibits at the world's fair. — Mon. Wea. Rev. **32**, 411–412.

Staff Members, 1947: On the general circulation of the atmosphere in middle latitudes. Staff Members of the Dept. of Meteor. of the University of Chicago. — Bull. Amer. Meteor. Soc. **28**, 255–280.

Teisserenc de Bort, L., 1898: Resultats des ascensions de trois ballons-sondes lances à Trappes, le 8 juin. — Compt. Rend. Séances Acad. Sci. Paris **127**, 135–138.

— 1899: Sur la température et ses variations dans l'atmosphère libre, d'après les observation de quatre-vingt-dix ballons-sondes. — Compt. Rend. Séances Acad. Sci. Paris **129**, 417–420.

— 1902: Variations de la température de l'air libre dans la zone comprise entre 8 km et 13 km d'altitude. — Compt. Rend. Séances Acad. Sci. Paris **134**, 987–989.

— 1904: Sur la decroissance de température avec la hauteur dans la région de Paris d'après 5 années d'observations. — Compt. Rend. Séances Acad. Sci. Paris **138**, 42–45.

— 1908: The isothermal layer of the atmosphere. — Nature **78**, 550–552.

— 1909: Lois de distribution de la température avec la hauteur aux diverses latitudes, et suivant les régimes météorologiques différents. — Compt. Rend. Séances Acad. Sci. Paris **148**, 591–594. (German translation: Die Gesetze der vertikalen Temperaturverteilung unter verschiedenen Breiten und bei verschiedenen meteorologischen Verhältnissen. — Meteor. Z. **26**, 267–270).

U.S. Weaether Bureau, 1957: Manual of radiosonde observations. Circular P, 7th ed. — U.S. Dept. of Commerce, Washington, D.C.

Wagner, A., 1910: Die Temperaturverhältnisse in der freien Atmosphäre. — Beitr. Phys. fr. Atmos. **3**, 57–167.

— 1936: Klimatologie der freien Atmosphär. Teil F des 1. Bandes des Handbuches der Klimatologie von Köppen und Geiger, Berlin. F1–F70.

Wegener, A., 1911: Neuere Forschungen auf dem Gebiet der atmosphärischen Physik. — Fortschritte der naturwissenschaftlichen Forschung, Hrsg. E. Abderhalden, Berlin. 1–70.

Weickmann, L., 1938: Hugo Hergesell. — Meteor. Z. **55**, 233–237.

WMO, 1957: Definition of the tropopause. — World Meteorological Organization, Bull. **6**, 136.

— 1986: Atmospheric ozone 1985: Global ozone research and monitoring report, Rep. No. 16. World Meteorological Organization, Geneva, Switzerland, 392 pp.

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